



FORM PTO-1390 (Modified) (REV 11-2000)		U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE		ATTORNEY'S DOCKET NUMBER <b>217483US2PCT</b>	
<b>TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371</b>				U.S. APPLICATION NO. (IF KNOWN, SEE 37 CFR <b>10/019440</b>	
INTERNATIONAL APPLICATION NO. <b>PCT/EP00/06133</b>		INTERNATIONAL FILING DATE <b>30 June 2000</b>		PRIORITY DATE CLAIMED <b>30 June 1999</b>	
TITLE OF INVENTION <b>PIEZOELECTRIC DRIVE, ESPECIALLY PIEZOELECTRIC MOTOR FOR PRODUCING CONTINUOUS OR STEPWISE MOVEMENTS, FRICTION ELEMENT FOR A PIEZOELECTRIC DRIVE FOR TRANSMISSION OF FORCES BETWEEN STATOR AND ROTOR, AS WELL AS CIRCUIT ARRANGEMENT FOR OPERATING A PIEZOELECTRIC DRIVE, ESPECIALLY A PIEZOELECTRIC MOTOR</b>					
APPLICANT(S) FOR DO/EO/US <b>WISCHNEWSKIY Wladimir</b>					
Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:					
<ol style="list-style-type: none"><li>1. <input checked="" type="checkbox"/> This is a <b>FIRST</b> submission of items concerning a filing under 35 U.S.C. 371.</li><li>2. <input type="checkbox"/> This is a <b>SECOND</b> or <b>SUBSEQUENT</b> submission of items concerning a filing under 35 U.S.C. 371.</li><li>3. <input checked="" type="checkbox"/> This is an express request to begin national examination procedures (35 U.S.C. 371(f)). The submission must include items (5), (6), (9) and (24) indicated below.</li><li>4. <input checked="" type="checkbox"/> The US has been elected by the expiration of 19 months from the priority date (Article 31).</li><li>5. <input checked="" type="checkbox"/> A copy of the International Application as filed (35 U.S.C. 371 (c) (2))<ol style="list-style-type: none"><li>a. <input type="checkbox"/> is attached hereto (required only if not communicated by the International Bureau).</li><li>b. <input checked="" type="checkbox"/> has been communicated by the International Bureau.</li><li>c. <input type="checkbox"/> is not required, as the application was filed in the United States Receiving Office (RO/US).</li></ol></li><li>6. <input checked="" type="checkbox"/> An English language translation of the International Application as filed (35 U.S.C. 371(c)(2)).<ol style="list-style-type: none"><li>a. <input checked="" type="checkbox"/> is attached hereto.</li><li>b. <input type="checkbox"/> has been previously submitted under 35 U.S.C. 154(d)(4).</li></ol></li><li>7. <input checked="" type="checkbox"/> Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371 (c)(3))<ol style="list-style-type: none"><li>a. <input type="checkbox"/> are attached hereto (required only if not communicated by the International Bureau).</li><li>b. <input type="checkbox"/> have been communicated by the International Bureau.</li><li>c. <input type="checkbox"/> have not been made; however, the time limit for making such amendments has NOT expired.</li><li>d. <input checked="" type="checkbox"/> have not been made and will not be made.</li></ol></li><li>8. <input type="checkbox"/> An English language translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).</li><li>9. <input type="checkbox"/> An oath or declaration of the inventor(s) (35 U.S.C. 371 (c)(4)).</li><li>10. <input type="checkbox"/> An English language translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371 (c)(5)).</li><li>11. <input type="checkbox"/> A copy of the International Preliminary Examination Report (PCT/IPEA/409).</li><li>12. <input checked="" type="checkbox"/> A copy of the International Search Report (PCT/ISA/210).</li></ol> <p><b>Items 13 to 20 below concern document(s) or information included:</b></p> <ol style="list-style-type: none"><li>13. <input checked="" type="checkbox"/> An Information Disclosure Statement under 37 CFR 1.97 and 1.98.</li><li>14. <input type="checkbox"/> An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.</li><li>15. <input type="checkbox"/> A <b>FIRST</b> preliminary amendment.</li><li>16. <input type="checkbox"/> A <b>SECOND</b> or <b>SUBSEQUENT</b> preliminary amendment.</li><li>17. <input type="checkbox"/> A substitute specification.</li><li>18. <input type="checkbox"/> A change of power of attorney and/or address letter.</li><li>19. <input type="checkbox"/> A computer-readable form of the sequence listing in accordance with PCT Rule 13ter.2 and 35 U.S.C. 1.821 - 1.825.</li><li>20. <input type="checkbox"/> A second copy of the published international application under 35 U.S.C. 154(d)(4).</li><li>21. <input type="checkbox"/> A second copy of the English language translation of the international application under 35 U.S.C. 154(d)(4).</li><li>22. <input type="checkbox"/> Certificate of Mailing by Express Mail</li><li>23. <input checked="" type="checkbox"/> Other items or information: <b>Notice of Priority/Form PTO-1449</b> <b>Drawings (16 sheets)</b></li></ol>					

U.S. APPLICATION NO. (IF KNOWN, SEE 37 CFR 1.101) <b>10/019440</b>		INTERNATIONAL APPLICATION NO. <b>PCT/EP00/06133</b>		ATTORNEY'S DOCKET NUMBER <b>217483US2PCT</b>	
24. The following fees are submitted: <b>BASIC NATIONAL FEE (37 CFR 1.492 (a) (1) - (5)) :</b> <input type="checkbox"/> Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO and International Search Report not prepared by the EPO or JPO ..... <b>\$1040.00</b> <input checked="" type="checkbox"/> International preliminary examination fee (37 CFR 1.482) not paid to USPTO but International Search Report prepared by the EPO or JPO ..... <b>\$890.00</b> <input type="checkbox"/> International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO ..... <b>\$740.00</b> <input type="checkbox"/> International preliminary examination fee (37 CFR 1.482) paid to USPTO but all claims did not satisfy provisions of PCT Article 33(1)-(4) ..... <b>\$710.00</b> <input type="checkbox"/> International preliminary examination fee (37 CFR 1.482) paid to USPTO and all claims satisfied provisions of PCT Article 33(1)-(4) ..... <b>\$100.00</b> <b>ENTER APPROPRIATE BASIC FEE AMOUNT =</b>				<b>CALCULATIONS PTO USE ONLY</b>	
Surcharge of <b>\$130.00</b> for furnishing the oath or declaration later than <input type="checkbox"/> 20 <input checked="" type="checkbox"/> 30 months from the earliest claimed priority date (37 CFR 1.492 (e)).				<b>\$890.00</b>	
CLAIMS NUMBER FILED NUMBER EXTRA RATE				<b>\$130.00</b>	
Total claims - 20 = 0 x \$18.00				<b>\$0.00</b>	
Independent claims - 3 = 0 x \$84.00				<b>\$0.00</b>	
Multiple Dependent Claims (check if applicable) <input type="checkbox"/>				<b>\$0.00</b>	
<b>TOTAL OF ABOVE CALCULATIONS =</b>				<b>\$1,020.00</b>	
<input type="checkbox"/> Applicant claims small entity status. See 37 CFR 1.27). The fees indicated above are reduced by 1/2.				<b>\$0.00</b>	
<b>SUBTOTAL =</b>				<b>\$1,020.00</b>	
Processing fee of <b>\$130.00</b> for furnishing the English translation later than <input type="checkbox"/> 20 <input type="checkbox"/> 30 months from the earliest claimed priority date (37 CFR 1.492 (f)).				<b>\$0.00</b>	
<b>TOTAL NATIONAL FEE =</b>				<b>\$1,020.00</b>	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31) (check if applicable). <input type="checkbox"/>				<b>\$0.00</b>	
<b>TOTAL FEES ENCLOSED =</b>				<b>\$1,020.00</b>	
				<b>Amount to be refunded</b> \$	
				<b>charged</b> \$	
a. <input checked="" type="checkbox"/> A check in the amount of <b>\$1,020.00</b> to cover the above fees is enclosed.					
b. <input type="checkbox"/> Please charge my Deposit Account No. _____ in the amount of _____ to cover the above fees. A duplicate copy of this sheet is enclosed.					
c. <input checked="" type="checkbox"/> The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. <b>15-0030</b> A duplicate copy of this sheet is enclosed.					
d. <input type="checkbox"/> Fees are to be charged to a credit card. <b>WARNING:</b> Information on this form may become public. <b>Credit card information should not be included on this form.</b> Provide credit card information and authorization on PTO-2038.					
<b>NOTE:</b> Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.					
SEND ALL CORRESPONDENCE TO:					
<div><div><div>Surinder Sachar Registration No. 34,423</div><div> <b>22850</b></div></div><div><div> SIGNATURE <b>Marvin J. Spivak</b> NAME <b>24,913</b> REGISTRATION NUMBER <b>Dec. 31 2001</b> DATE</div></div></div>					

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Rec'd PCT/PTO 17 AUG 2002

#7/a

217483US

IN THE UNITED STATES PATENT & TRADEMARK OFFICE

IN RE APPLICATION OF :  
WLADIMIR WISCHNEWSKIY : ATTN: APPLICATION DIVISION  
SERIAL NO: 10/019,440 :  
FILED: 31 December 2001 :  
FOR: PIEZOELECTRIC DRIVE, :  
ESPECIALLY PIEZOELECTRIC  
MOTOR FOR PRODUCING  
CONTINUOUS OR STEPWISE  
MOVEMENTS, FRICTION ELEMENT  
FOR A PIEZOELECTRIC DRIVE FOR  
TRANSMISSION OF FORCES BETWEEN  
STATOR AND ROTOR, AS WELL AS  
CIRCUIT ARRANGEMENT FOR  
OPERATING A PIEZOELECTRIC DRIVE,  
ESPECIALLY A PIEZOELECTRIC MOTOR

PRELIMINARY AMENDMENT

ASSISTANT COMMISSIONER FOR PATENTS  
WASHINGTON, D.C. 20231

SIR:

Prior to a first examination on the merits, please amend the above-identified  
application as follows:

IN THE TITLE

Please delete the current title and insert therefor:

PIEZOELECTRIC DRIVE, ESPECIALLY A HOLDING FRAME, A FRICTION ELEMENT  
AND A CIRCUIT CONFIGURATION

IN THE CLAIMS

Please amend the claims as follows:

3. (Amended) A piezoelectric drive according to claim 1,  
characterized in that  
two oppositely disposed stays or bridges are provided, and in that a spacing gap is  
formed between the longitudinal broad sides of the transducer and the inner frame.
4. (Amended) A piezoelectric drive according to claim 1,  
characterized in that  
the double frame is made of a high-quality metal material.
5. (Amended) A piezoelectric drive according to claim 1,  
characterized in that  
the inner frames are each fastened by continuous material to the transducer.
9. (Amended) A friction element according to claim 6,  
characterized in that  
the interface of the double-layer structure is oriented substantially parallel to the end  
face of the transducer.
10. (Amended) A friction element according to claim 6,  
characterized by  
the use thereof for a piezoelectric drive, especially a piezoelectric motor for  
producing continuous or stepwise movements, comprising a rotor provided with a friction  
surface, a drive element in the form of a piezoelectric exciter that can be brought into contact  
with this surface, the exciter comprising a monolithic, plate-like, piezoelectric transducer  
provided with substantially rectangular electrode faces, an outer fastening, a friction element  
disposed on one of the end faces of the piezoelectric transducer, as well as a holding device

for the piezoelectric transducer and means for pressing the friction element elastically against the friction surface, characterized in that

an elastic double frame enclosing the transducer and having inner and outer frames is disposed at each outer node of the bending oscillation mode for the purpose of holding the piezoelectric transducer and for producing the pressing force of the friction element, the inner frame being joined to each of the longitudinal narrow sides of the transducer and the outer frame to the outer fastening, and furthermore the outer frame and inner frame being spaced apart and maintained in contact via stays or bridges.

14. (Amended) A circuit arrangement according to claim 11, characterized in that

a bending sensor for determination of mechanical strictions is disposed on the piezoelectric transducer, the bending-sensor electrodes being connected via a signal-evaluation unit to a control input of the primary generator.

16. (Amended) A circuit arrangement according to claim 14, characterized in that

the bending sensor for determination of the bending components of the mechanical excitation is constructed as a thin, single-layer piezoceramic plate with electrodes covering the entire main surface and is polarized symmetrically relative to the transverse axis, the bending sensor being rigidly joined to one of the transducer surfaces between middle and side nodes of the bending mode of the oscillations.

17. (Amended) A circuit arrangement according to claim 11, characterized by

the use thereof for activation of a piezoelectric drive, especially a piezoelectric motor for producing continuous or stepwise movements, comprising a rotor provided with a friction surface, a drive element in the form of a piezoelectric exciter that can be brought into contact

with this surface, the exciter comprising a monolithic, plate-like, piezoelectric transducer provided with substantially rectangular electrode faces, an outer fastening, a friction element disposed on one of the end faces of the piezoelectric transducer, as well as a holding device for the piezoelectric transducer and means for pressing the friction element elastically against the friction surface, characterized in that

an elastic double frame enclosing the transducer and having inner and outer frames is disposed at each outer node of the bending oscillation mode for the purpose of holding the piezoelectric transducer and for producing the pressing force of the friction element, the inner frame being joined to each of the longitudinal narrow sides of the transducer and the outer frame to the outer fastening, and furthermore the outer frame and inner frame being spaced apart and maintained in contact via stays or bridges.

#### IN THE ABSTRACT OF THE DISCLOSURE

Please amend the abstract on page 41 as follows:

#### ABSTRACT

A piezoelectric drive, especially a piezoelectric motor for producing continuous or stepwise movements, a friction element for such a piezoelectric drive as well as for transmission of forces between stator and rotor, and a circuit arrangement for operating a piezoelectric drive, especially a piezoelectric motor. An elastic double frame enclosing the transducer and having inner and outer frames is disposed at each outer node of the bending oscillation mode to hold the piezoelectric transducer and produce the pressing force of the friction element. The inner frame is joined to each of the longitudinal narrow sides of the transducer and the outer frame to the outer fastening. Further, the outer frame and inner frame are spaced apart and maintained in contact by stays or bridges. The friction element is

constructed as a double-layer structure with a first hard, porous member joined to the transducer, and with a second part or member including an abrasion-resistant monolithic material maintained in contact with the rotor, the two layers being bonded by sintering. The circuit arrangement for operation of the drive relies on a special bridge power amplifier as well as on the capability of compensating for temperature variation of the drive for stable operation thereof.

## REMARKS

Favorable consideration of the above-identified application, as presently amended, is respectfully requested.

The present preliminary amendment is submitted to place the above-identified application in more proper format under U. S. practice.

The title is amended by the present response to match that on the application publication sheet.

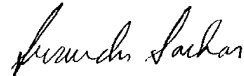
The claims are amended to no longer recite any improper multiple dependencies.

A new Abstract believed to be in more proper format under United States practice is also submitted herein.

The present application is believed to be in condition for a full and thorough examination on the merits. An early and favorable consideration of the present application is hereby respectfully requested.

Respectfully submitted,

OBLON, SPIVAK, McCLELLAND,  
MAIER & NEUSTADT, P.C.



Gregory J. Maier  
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Rec'd PCT/PTO 17 AUG 2002

217483US

<b>Marked-Up Copy</b> Serial No: 10/019,440 Amendment Filed on: 4-17-2002
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IN THE TITLE

Please delete the current title and insert therefor:

--[PIEZOELECTRIC DRIVE, ESPECIALLY PIEZOELECTRIC MOTOR FOR  
 PRODUCING CONTINUOUS OR STEPWISE MOVEMENTS, FRICTION ELEMENT  
 FOR A PIEZOELECTRIC DRIVE FOR TRANSMISSION OF FORCES BETWEEN  
 STATOR AND ROTOR, AS WELL AS CIRCUIT ARRANGEMENT FOR OPERATING A  
 PIEZOELECTRIC DRIVE, ESPECIALLY A PIEZOELECTRIC MOTOR]  
PIEZOELECTRIC DRIVE, ESPECIALLY A HOLDING FRAME, A FRICTION  
ELEMENT AND A CIRCUIT CONFIGURATION--

IN THE CLAIMS

Please amend the claims as follows:

- 3. (Amended) A piezoelectric drive according to claim 1 [or 2],  
 characterized in that  
 two oppositely disposed stays or bridges are provided, and in that a spacing gap is  
 formed between the longitudinal broad sides of the transducer and the inner frame.
4. (Amended) A piezoelectric drive according to [one of the preceding claims] claim  
 1,

characterized in that

the double frame is made of a high-quality metal material.

5. (Amended) A piezoelectric drive according to [one of the preceding claims] claim 1,

characterized in that

the inner frames are each fastened by continuous material to the transducer.

9. (Amended) A friction element according to [one of claims 6 to 8] claim 6,

characterized in that

the interface of the double-layer structure is oriented substantially parallel to the end face of the transducer.

10. (Amended) A friction element according to [one of claims 6 to 9] claim 6,

characterized by

the use thereof for a piezoelectric drive [according to the features of at least one of claims 1 to 5], especially a piezoelectric motor for producing continuous or stepwise movements, comprising a rotor provided with a friction surface, a drive element in the form of a piezoelectric exciter that can be brought into contact with this surface, the exciter comprising a monolithic, plate-like, piezoelectric transducer provided with substantially rectangular electrode faces, an outer fastening, a friction element disposed on one of the end faces of the piezoelectric transducer, as well as a holding device for the piezoelectric transducer and means for pressing the friction element elastically against the friction surface, characterized in that

an elastic double frame enclosing the transducer and having inner and outer frames is disposed at each outer node of the bending oscillation mode for the purpose of holding the piezoelectric transducer and for producing the pressing force of the friction element, the inner

frame being joined to each of the longitudinal narrow sides of the transducer and the outer frame to the outer fastening, and furthermore the outer frame and inner frame being spaced apart and maintained in contact via stays or bridges.

14. (Amended) A circuit arrangement according to [one of claims 11 to 13] claim 11,

characterized in that

a bending sensor for determination of mechanical strictions is disposed on the piezoelectric transducer, the bending-sensor electrodes being connected via a signal-evaluation unit to a control input of the primary generator.

16. (Amended) A circuit arrangement according to claim 14 [or 15],

characterized in that

the bending sensor for determination of the bending components of the mechanical excitation is constructed as a thin, single-layer piezoceramic plate with electrodes covering the entire main surface and is polarized symmetrically relative to the transverse axis, the bending sensor being rigidly joined to one of the transducer surfaces between middle and side nodes of the bending mode of the oscillations.

17. (Amended) A circuit arrangement according to [one of claims 11 to 16] claim 11, characterized by

the use thereof for activation of a piezoelectric drive [according to one of claims 1 to 5], especially a piezoelectric motor for producing continuous or stepwise movements, comprising a rotor provided with a friction surface, a drive element in the form of a piezoelectric exciter that can be brought into contact with this surface, the exciter comprising a monolithic, plate-like, piezoelectric transducer provided with substantially rectangular electrode faces, an outer fastening, a friction element disposed on one of the end faces of the

piezoelectric transducer, as well as a holding device for the piezoelectric transducer and means for pressing the friction element elastically against the friction surface, characterized in that

an elastic double frame enclosing the transducer and having inner and outer frames is disposed at each outer node of the bending oscillation mode for the purpose of holding the piezoelectric transducer and for producing the pressing force of the friction element, the inner frame being joined to each of the longitudinal narrow sides of the transducer and the outer frame to the outer fastening, and furthermore the outer frame and inner frame being spaced apart and maintained in contact via stays or bridges.--

#### IN THE ABSTRACT OF THE DISCLOSURE

Please amend the abstract on page 41 as follows:

[Abstract]                    ABSTRACT

[The invention relates to a] A piezoelectric drive, especially a piezoelectric motor for producing continuous or stepwise movements, [to] a friction element for such a piezoelectric drive as well as for transmission of forces between stator and rotor, [as well as to] and a circuit arrangement for operating a piezoelectric drive, especially a piezoelectric motor. An elastic double frame enclosing the transducer and having inner and outer frames is disposed at each outer node of the bending oscillation mode [for the purpose of holding] to hold the piezoelectric transducer and [for producing] produce the pressing force of the friction element[, the] . The inner frame [being] is joined to each of the longitudinal narrow sides of the transducer and the outer frame to the outer fastening[, and furthermore] . Further, the outer frame and inner frame [being] are spaced apart and maintained in contact [via] by stays or bridges. The [inventive] friction element is constructed as a double-layer structure with a

first hard, porous member joined to the transducer, and with a second part or member [comprising] including an abrasion-resistant monolithic material maintained in contact with the rotor, the two layers being bonded by sintering. The circuit arrangement for operation of the drive relies on a special bridge power amplifier as well as on the capability of compensating for [the] temperature variation of the drive for [the purpose of] stable operation thereof.--

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10/019440  
JC13 Rec'd PCT/PTO 31 DEC 2001

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Piezoelectric drive, especially piezoelectric motor  
for producing continuous or stepwise movements,  
friction element for a piezoelectric drive for  
transmission of forces between stator and rotor, as well as  
circuit arrangement for operating a piezoelectric  
drive, especially a piezoelectric motor

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#### Specification

The invention relates to a piezoelectric drive, especially a piezoelectric motor for producing continuous or stepwise movements, comprising a rotor provided with a friction surface, a drive element in the form of a piezoelectric exciter that can be brought into contact with this surface, the exciter comprising a monolithic, plate-like, piezoelectric transducer provided with substantially rectangular electrode faces, an outer fastening, a friction element disposed on one of the end faces of the piezoelectric transducer, as well as a holding device for the piezoelectric transducer and means for pressing the friction element elastically against the friction surface of the rotor. The invention also relates to a friction element for a piezoelectric drive for transmitting forces between stator and rotor as well as to a circuit arrangement for operating a piezoelectric drive, especially a piezoelectric motor according to the preamble of claims 1, 6 and 11.

Piezoelectric motors which comprise a stator and rotor and wherein the stator is provided with at least one piezoelectric oscillator that can be pressed frictionally against the surface of the rotor in drive direction are known. The oscillator comprises in known manner a piezo element provided on its parallel outside faces with electrodes, which are connected to an a.c. voltage source. An example of the prior art can be found in German Patent 2530045 C2.

From European Patent Application 0475752 there are known linear piezoelectric motors which rely functionally on acoustic traveling waves. As is also shown in US Patent 5596241, such motors have the disadvantage that they cannot be miniaturized, since the minimum length of the waveguide must be an integral multiple of the wavelength  $\lambda$ . Furthermore, such motors are structurally complex, technologically difficult to reduce to practice and therefore expensive.

Piezoelectric motors based on standing waves are also known in the prior art, as evidenced by US Patent 5714833. In such motors a piezoelectric exciter tuned to the second bending mode and the first longitudinal mode of the acoustic oscillations is used as the drive element. The exciter is provided with a plate-like piezoelectric piezotransducer, which is equipped with two electrode groups for generation of oscillations and on the end face of which there is disposed a friction element. Transverse displacement of the exciter is limited by means of a special holding device.

The friction surface of the exciter is pressed elastically against the corresponding friction surface of the rotor by means of a pressing component, such as a spring.

As shown in US Patent 5714833, the component for producing the pressing force of the exciter and the transverse holding device of the exciter are constructed as mutually separate subassemblies. The known transverse holding device has the form of two rigid and two elastic carriers, which are disposed on the sides of the piezotransducer. The elastic carriers press the piezotransducer against the rigid carriers, such as studs disposed in a cavity of the piezotransducer, thus achieving appropriate fixation in transverse direction. The rigid carriers are constructed, for example, as conical plastic elements or plastic pins, the elastic carriers being made of rubber-like materials. The actual component for pressing the exciter or a friction element against the rotor surface comprises a spring

braced by a rear housing wall against the second end surface of the piezotransducer.

In the teaching of the solution known from US Patent 5714833 described hereinabove, it is a substantial disadvantage that the two carrier types, the holding device and the pressing component of the exciter have poor mechanical quality and a high coefficient of friction with the surface of the piezotransducer. As a result of these facts, undesired heating occurs during operation of a motor constructed in this way, due both to the internal friction of the element and to friction at the surfaces of the oscillating transducer. Undesired heating of the piezotransducer not only reduces the efficiency of the motor but also leads to unstable operation.

A further substantial disadvantage of the known solution, which comprises a carrier made of plastic materials and rubber-like materials, is the unilateral, rigid fastening, which does not permit precise positioning, especially at high rotor velocities. In such motors it has been observed that strong unilateral runout of the rotor occurs, reaching several tenths of one micrometer, which is unacceptably large for many applications. Thus the drive cannot be regarded as a precision drive. Ultimately the transverse holding device and the pressing component put mechanical stress on the exciter, thus adding a further active resistance to its resonance system. This in turn necessitates an increase of the exciter voltage to 500 V, in turn entailing special protective measures. Furthermore, the frequency range of optimal motor operation as regards the mechanical resonance frequency of the bending mode of the oscillator vibrations shifts on the frequency scale, and so frequency stabilization of the working point by means of phase feedback becomes impossible.

From German Patent 19648726 A1 there is known a piezoelectric drive element with at least one oscillator comprising piezoelectric ceramic or attached piezoelectric exciters that is



movable in x-, y- or z-direction, the at least one oscillator being fastened to an oscillator holder. According to the solution therein, the oscillator holder is fastened by means of spring bearings, especially bending spring linkages, to a carrier part in such a way that the movement of the at least one oscillator or of the oscillator holder in the y- and z-direction can be suppressed, while the desired movement in the x-direction can take place with the least possible perturbation. According to German Patent 19648726 A1, the oscillator holder, bending spring linkages and carrier part are constructed in one piece as a monolithic subassembly.

It has been shown, however, that the arrangement cited hereinabove for a piezoelectric drive element tends to material fatigue during prolonged operation due to the forces acting in the region of the bending spring linkages and that a permanent predetermined brake point exists in the transition region between oscillator holder and bending spring linkage.

From the foregoing, one object of the invention is to provide a further-developed piezoelectric drive, especially a piezoelectric motor for production of continuous or stepwise movements, wherein the efficiency and long-term stability of the drive are improved by a special holding device such that precise translational movements and fine positioning adjustments, such as for microscope or coordinate tables, can be achieved under all circumstances. Another object of the invention is to prevent undesired heating of the exciter, so that motor operation can be stabilized.

A further object of the invention is to improve the friction elements known in themselves for a piezoelectric drive for transmission of forces between stator and rotor to the effect that, on the one hand, the friction element is joined in firmly adhering manner to the piezo oscillator or exciter and, on the other hand, the outer contact surface satisfies all requirements of wear resistance and reliable driving of the rotor.

Ultimately it is the object of the invention to provide a circuit arrangement for operation of a piezoelectric drive, especially a piezoelectric motor, by means of which the working point of the motor can be stabilized while at the same time the exciter voltage remains low.

The object of the invention is achieved with subject matter according to the features of claim 1 as it relates to the piezoelectric drive and the special holding device of the piezoelectric transducer, with a double-layer structure according to the definition of claim 6 as it relates to the improved friction element, and with a teaching according to the features of claim 11 as it relates to the circuit arrangement for operation of a piezoelectric drive, the dependent claims respectively comprising at least expedient embodiments and improvements.

The basic idea of the invention with respect to the piezoelectric drive and the holding device necessary therefor is that it be designed such that the actual transverse holding device of the piezoelectric transducer or oscillator is combined with the function of elastic pressing of the friction element against the rotor surface.

Specifically, an elastic double frame enclosing the transducer and having inner and outer frames is disposed at each outer node of the bending oscillation mode for the purpose of holding the piezoelectric transducer and for producing the desired pressing force of the friction element.

The inner frame is joined to each of the longitudinal narrow sides of the transducer and the outer frame to the outer fastening.

The outer and inner frames are spaced apart from one another and are maintained in contact via stays or bridges. The double frames are made of high-quality elastic material.

Preferably the double frames respectively have a structure that is symmetric along the axes, while the stays or bridges joining the inner and outer frames are centrally disposed.

Since, as described hereinabove, each inner frame is joined rigidly with its narrow sides to the longitudinal narrow sides, or in other words the smaller side faces of the plate-like piezoelectric transducer, and each outer frame is joined rigidly to the outer fastening, such as a housing, and since bridging structures are present between inner and outer frames, each of the two double frames becomes a high-quality bending-oscillation element. In the proposed construction, no mutual movements exist between the vibrating or oscillating surfaces of the piezoelectric exciter and the inner-frame surfaces joined rigidly thereto, and so no mechanical friction losses occur.

The internal friction losses of the double frames themselves are extremely small, since the frames are made from materials of high mechanical quality. The transverse holding device of the piezoelectric exciter and the fixture combined therewith for elastic pressing of the exciter or the friction element disposed thereon exhibits very small mechanical losses. Together with the double-frame holding devices, the exciter, or in other words the oscillator forms a common oscillating system having small mechanical losses. The carrier does not become heated and thus has a great degree of stability during operation. By virtue of the much smaller mechanical losses, the efficiency of the motor is greater than that of known solutions, and smaller exciting voltages are possible.

Ultimately the inner and outer frames have great rigidity in their transverse directions, and so transverse displacements of the exciter during positioning of the rotor with high velocity can be ruled out, meaning in principle that positioning precision equal to the smallest oscillation step of the exciter is

possible.

To maintain the desired properties of the exciter or oscillator in combination with its holding device, spacing gaps are provided between the longitudinal broad sides of the transducer and the respective inner frames. Preferably the inner frames are connected by continuous material to the longitudinal narrow sides of the transducer, by adhesive bonding, soldering or similar types of joining.

As regards the friction element for a piezoelectric drive for transmission of forces between stator and rotor, a further basic idea of the invention relies on a double-layer structure.

The part of the layer structure joined to the transducer or exciter is formed as a hard, porous member, while the part of the layer structure maintained in contact with the rotors comprises an abrasion-resistant monolithic member. The two layers or the two members are joined to one another by sintering.

Fillers for maintaining a firm bond between the transducer surface and the actual friction element are disposed on or introduced into the pores of the part of the layer structure joined to the transducer.

Examples of usable fillers are epoxy resin and/or low melting glasses. Preferably the interface of the double-layer structure is oriented substantially parallel to the end face of the transducer.

The friction element with double-layer structure can be constructed either as a square or even as a flat or steep truncated pyramid or conical member.

In an embodiment fashioned as a truncated pyramid, the joining surface between friction element and exciter is enlarged, so that the adhesion achieved here can be increased and greater forces can be transmitted.

The circuit arrangement for operation of a piezoelectric drive, especially a piezoelectric motor, is in principle a primary or control generator that cooperates with a two-channel bridge power amplifier. A first output of the power amplifier is connected directly to the output of the primary or control generator, while the second output is connected to the primary generator via a phase shifter. A filter as well as a summing transformer is looped into the output diagonals of the bridge power amplifier, the secondary winding of the transformer being contacted via a changeover switch with one of the electrode faces, known in themselves, of the piezoelectric transducer. Linear velocity regulation of the drive or of the motor operation can be achieved with such a circuit arrangement.

In a further embodiment of the circuit arrangement for operation of a piezoelectric drive, there are additionally provided a signal-level transducer, a comparator and an electronic electrode-group commutator. In this case the input of the signal-level transducer is connected to the comparator input and the output of the signal-level transducer is connected to the phase-control input of the phase shifter. The comparator outputs are connected to the control inputs of the electrode-group commutator, while the outputs of the commutator are connected to the respective electrode faces. In this embodiment, activation of the motor can be achieved in unipolar operation.

In a further embodiment of the invention, a bending sensor for measurement of the bending components of the mechanical excitation is disposed on the piezoelectric transducer or exciter, the bending sensor being formed as a thin, one-layer piezoceramic plate. The piezoceramic plate of the bending sensor has bidirectional polarization, which is perpendicular and symmetric relative to its transverse axis. The plate itself is fastened rigidly to the surface of the piezoelectric transducer,

preferably midway between the center and side nodes of the bending mode of the oscillations.

In this embodiment, it is possible to obtain a measured signal whose phase shift is directly proportional to the change of the mechanical bending stresses or to the velocity of oscillation of the exciter.

In this embodiment of the piezoelectric motor with bending sensor, a phase detector with a reference-signal input, a control input and an output is provided in the circuit arrangement. The primary generator has an input for electrical control of the excitation frequency. One of the groups of electrode faces of the transducer is connected to the reference-signal input of the phase detector via a reference-signal generating device. The bending-sensor electrodes are connected to the input of the reference-signal generator, whose output is contacted with the control input of the phase detector. The output of the phase detector in turn is connected to the input for activation of the excitation frequency of the primary generator.

In this alternative embodiment of the circuit, there is provided negative frequency feedback, whereby stabilization of the motor operation is made possible in a broad temperature range.

The invention will be explained in more detail hereinafter on the basis of practical examples and with reference to figures, wherein:

Fig. 1 shows a block diagram of the piezoelectric drive in an embodiment as a linear motor;

Fig. 2 shows a diagram of the basic construction of the piezoelectric transducer or oscillator;

- Figs. 3 and 4 show a diagram of the construction of the double frames in side view and top view respectively;
- Figs. 5 and 6 show a diagram of the joint between the inner frame of the double-frame arrangement and the plate-like piezoelectric transducer;
- Fig. 7 shows a top view of the motor construction in the embodiment as a linear drive;
- Fig. 8 shows a diagram of the resultant forces which occur on the elastic double frame during operation of the motor;
- Figs. 9 and 10 show diagrams of forms of oscillation of the faces of the elastic double frame;
- Fig. 11 shows different alternative embodiments with respect to the geometric layout of the friction element;
- Fig. 12 shows an embodiment of the circuit arrangement for operation of a piezoelectric drive, including a block diagram of the transducer with double-frame holding device;
- Fig. 13 shows a diagram of the excitation behavior in association with the variation of substantially sinusoidal activating voltages;
- Fig. 14 shows explanatory diagrams with respect to the operating principle of the circuit arrangement;
- Fig. 15 shows a further embodiment of the circuit arrangement for operation of a piezoelectric drive with signal-level transducer;

- Fig. 16 shows explanatory diagrams with respect to the operating principle of the circuit arrangement according to a practical example;
- Fig. 17 shows a diagram of the basic design and arrangement of the bending sensor for determination of the bending components of the mechanical exciter oscillations;
- Fig. 18 shows explanatory diagrams with respect to the working principle of the bending sensor, and
- Fig. 19 shows a further alternative embodiment of the circuit for activation of a piezoelectric drive with piezoelectric transducer as bending sensor, for the purpose of stabilizing motor operation in a broad temperature range.

The piezoelectric drive illustrated in an embodiment as a linear motor in Fig. 1 comprises a rotor with a friction surface and a drive element or a corresponding drive unit that can be brought into contact with this surface. The drive element is designed in the form of a piezoelectric exciter, the exciter comprising in a manner known in itself a monolithic, plate-like piezoelectric transducer with substantially rectangular electrode faces. An outer fastening, which can also be part of a housing, is also provided.

A friction element is disposed on one of the end faces of the piezoelectric transducer, and there is provided for the piezoelectric transducer a special holding device, which simultaneously permits the friction element to be pressed elastically against the friction surface of the rotor. To hold the piezoelectric transducer and to produce the pressing force of the friction element, an elastic double frame with inner and outer frames, enclosing the transducer, is disposed respectively at the outer nodes of the bending-oscillation mode.



The inner frame is joined respectively to the longitudinal narrow sides of the transducer, and the outer frame is joined to the outer fastening, which can be part of a housing. The outer frame and the inner frame are spaced apart and are in contact via stays or bridges. The double frame is of one-piece construction and can be made from a metallic material by electroerosion, etching, laser cutting or similar techniques.

According to Fig. 1 there is provided a rotor 1, which has a friction surface 2. Rotor 1 is braced via bearings 3 against a carrier base 4.

A drive element 5 is joined in active elastic relationship to rotor 1. Drive element 5 is held in a housing 6.

In the illustrated example, housing 6 is fastened positively and nonpositively to carrier base 4 by means of screws. Oblong holes in housing 6 permit adjustment of the position of the housing and thus of drive element 5 relative to rotor 1.

Drive element 5 is constructed as a piezoelectric exciter 8, which contains a monolithic, plate-like piezoelectric transducer 9 as well as two electrode faces or electrode groups and a friction element 12 disposed on end surface 9.

The transverse fastening of piezoelectric transducer 9 and the pressing of friction element 12 against the friction surface 2 of rotor 1 is ensured by means of special double frames 13. These elastic double frames 13 enclose plate-like piezoelectric transducer 9 at both ends, in each case at the outer nodes of the bending-oscillation mode.

Each of the electrode groups or electrode faces 10, 11 is connected via appropriate terminal leads 16 to a circuit arrangement for activation.

On their outer side the double frames are detachably joined to the corresponding part of housing 6 by means of screws 14.

The basic construction of piezoelectric exciter 8 is illustrated in Fig. 2. Exciter 8 contains the monolithic, plate-like, piezoelectric transducer 9 with friction element 12. On the larger side faces of transducer 9 there are disposed flat electrodes, which are interconnected in groups 10, 11. Electrode group 10 is formed by the two upper electrodes 17 and 18 and one lower electrode 19 or rear-side electrode. Electrode group 11 comprises the oppositely disposed upper electrodes 20 and 21 as well as the lower or rear-side electrode 19. Electrodes 17, 21 as well as 18, 20 are constructed symmetrically relative to the longitudinal axis of plate-like piezoelectric transducer 9. Furthermore, electrodes 17 and 18 as well as 20 and 21 according to Fig. 2 are electrically interconnected diagonally in pairs. The piezoceramic disposed between the front-side and rear-side electrodes is polarized homogeneously and perpendicular to the electrode surfaces according to Fig. 2.

In the practical example, the length and width of piezoelectric transducer 9 are so selected that their ratio is about 3.7. This means that piezoelectric transducer 9 is tuned to the second bending oscillation mode and the first longitudinal oscillation mode.

The resonance frequencies of these oscillation modes are close to one another. For such a relationship between the resonance frequencies, the distribution of oscillation velocities for bending oscillations  $V_y$  and for longitudinal oscillations  $V_x$  varies along the centerline as shown in diagrams 22 and 23 of Fig. 2.

Over the length  $L$  of the plate-like piezotransducer there exist three nodes of the oscillation velocity of the bending mode of the oscillations in which the transverse component of the oscillation velocity  $V_y$  is equal to zero. The middle nodes are

located on line A at the center of plate-like transducer 9, while two outer nodes are located along lines B and C.

Elastic double frames 13, or in other words the inner frame part, are fastened at points 24 of the longitudinal narrow sides of plate-like piezoelectric transducer 9, which points simultaneously correspond to the outer nodes. These points are disposed on lines B and C, and are separated from the outer end surfaces of piezotransducer 9 by distance d. Distance d corresponds approximately to  $1/9$  to  $1/11$  L, the exact value being experimentally determinable.

Particulars of the construction of flat elastic double frames 13 are shown in Figs. 3 and 4. Each double frame 13 comprises an outer frame 25 and an inner frame 26. Outer and inner frames are separated by a gap and can move oscillatingly relative to one another. Outer frame 25 is joined to inner frame 26 by means of two centrally disposed bridges or stays 27. Between the two frames 25 and 26, and between inner frame 26 and the larger of the side surfaces of plate-like piezoelectric transducer 9, there exist the already mentioned gaps 28. Outer frame 25 is provided on both of its lateral faces 29 with bores or similar openings 30, which are used for fastening frame 13 to housing 6, for example by means of screws 14 (Fig. 1).

Flat elastic double frames 13 are preferably made of heat-treated beryllium bronze with a thickness of 0.1 to 0.5 mm or from a corresponding steel strip by means of laser cutting or chemical etching. The gaps between the frames are made in the same technological manufacturing cycle. The gap thickness ranges between 0.1 and 0.2 mm. The gaps 28 disposed between inner frame 26 and the larger sides of plate-like transducer 9 can range between 0.05 and 0.1 mm.

Inner frame 26, together with its lateral parts 31, is fastened rigidly, and in particular is joined by continuous material to

the respective longitudinal narrow sides, or in other words the smaller side faces of plate-like transducer 9. The points in question are denoted by reference symbols 24 according to Fig. 4.

The rigid fastening of the sides of inner frame 26 to the smaller side faces of plate-like piezotransducer 9 can be accomplished by adhesive bonding, wherein a drop 32 of epoxy resin (see Figs. 5 and 6) is applied directly onto the piezoceramic surface.

Alternatively a soldered joint can be made, in which case the sides of frame 26 are soldered by means of a soft solder to the metal intermediate layers applied beforehand on the piezoceramic. The metal intermediate layer can be applied on the surface of piezotransducer 9 at the appropriate points 24 by vacuum coating. Conceivable multi-layer structures are those of the chromium-copper-nickel or titanium-copper-nickel or similar types, which have good solderability and optimized bonding to the surface of the piezoceramic.

Fig. 7 shows a top view of a ready-to-use piezoelectric linear drive with an enlarged diagram of the quasi x-shaped deformation of double frames 13, the sides 29, 31 of the inner and outer frames being bent to a degree  $h$  in this case. The forces acting on double frames 13 or generated there will be explained in more detail with reference to Fig. 8.

During assembly of the piezoelectric drive, two secondary forces  $F_0$  (see Fig. 7) acting along the X-axis and disposed perpendicular to friction surface 2 of rotor 1 are produced. Friction element 12 is then braced on friction surface 2, and double frames 13 are pulled apart to the distances  $h$ . The distances  $h$  are determined by the elasticity of double frames 13 and resultant force  $2F_0$ . Force  $2F_0$  is adjusted to be equal to the force  $F_p$  which presses friction element 12 against friction

surface 1. Thereafter housing 6 is fastened to the base or to carrier 4 by means of screws 7.

As a result, two elasticity forces FS acting at the angle  $\alpha_f$  relative to the smaller side faces of plate-like piezotransducer 9 are developed in elastic double frames 13, as is evident from Fig. 8.

Secondary forces F0 are canceled after housing 6 has been fastened.

Points 24, at which double frames 13 are fastened to the smaller side faces of plate-like piezotransducer 9, function as the point of application of elasticity forces FS. Each of the elasticity forces FS is resolved into two components at points 24. One component is directed along the side face, and is denoted by F1. The second component is oriented perpendicular thereto and is denoted by Ft. The forces FS, F1 and Ft form the triangle of forces clearly shown in diagram 33.

Forces F1 are oriented in the direction of friction surface 2 of rotor 1. They press friction element 12 against friction surface 2, and so pressing force Fp is formed by the sum of the four forces F1.

In addition, forces F1 tend to shift transducer 9 relative to side face 29 of the double frames. Forces Ft are oriented opposite to one another and compress plate-like piezotransducer, thus counteracting forces F1 and fixing the transducer.

Relative to force F1, force Ft has a magnitude of about  $F_t = (F_1 \times H)/h$ . If, for example, the plate-like piezotransducer has dimensions of 37 x 10 x 3 mm and the friction element has dimensions of 3 x 3 x 4 mm, static pressing force Fp is about 10 N. If the double frames have a thickness of 0.3 mm and dimensions of 22 x 6 mm, the force of 10 N is developed when double frames 13 have been pulled apart to the distance of about  $h = 0.5$  mm.

This means that, for a pressing force  $F_p$  of 10 N, the two elasticity forces  $F_S$  form a compressive force of  $F_t = 12.5$  N, starting from middle frame 13.

For one side on double frame 13, the ratio  $F_t/F_l$  is equal to 3.125. This means that, with the proposed fixture and holding device for transverse fastening and for pressing the exciter under the influence of the static pressing force  $F_p$ , there results a static compressive force  $F_t$  which is directed perpendicular to the side faces of plate-like piezotransducer 9 and which is substantially larger than the displacement force  $F_l$ . Such quasi force transformation acts to achieve good and secure joining of the spring arrangement of the double frames to piezotransducer 9, without leading to development of highly stressed and thus predetermined break points.

In summary, Fig. 8 shows the force-induced effects produced in double frame 13 of the holding device. Forces  $F_S$  are the elasticity forces of plate-like double frames 13, which are directed along frames 13 and act on the longitudinal narrow sides of plate-like piezotransducer 9 at the angle  $\alpha_f$ . Each of the forces  $F_t$  is resolved into two forces, namely into the force  $F_l$ , which is directed perpendicular to friction surface 2 of rotor 1, and force  $F_t$ , which is directed perpendicular to the longitudinal narrow sides of piezotransducer 9. The sum of the forces  $F_l$  forms the pressing force  $F_p$ , which presses friction element 12 against friction surface 2. The pair of forces  $F_t$  compresses transducer 9 and fixes it.

Various oscillation forms are additionally shown in Figs. 9 and 10, the oscillations according to Fig. 9 being due to the influence of the bending mode and the oscillations according to Fig. 10 being due to that of the longitudinal mode of the exciter.

The friction element for the piezoelectric drive for transmitting

forces between stator and rotor has already been mentioned in the foregoing description of the practical example. This friction element is provided here with a double-layer structure, wherein the part of the layer structure bonded to the transducer is formed as a hard, porous member and the part of the layer structure in contact with the rotor is formed as an abrasion-resistant monolithic member, the two layers being firmly bonded to one another by sintering. Fillers to achieve a firm bond between the transducer surface on the one hand and the friction element on the other hand are disposed in or introduced into the pores of the part of the layer structure bonded to the transducer. Examples of these fillers are epoxy resin and/or low-melting glasses.

Alternative embodiments of the friction layer with double-layer structure are presented in Fig. 11. Diagram 34 shows a rectangular, diagram 35 a trapezoidal or truncated pyramidal and diagram 36 a conical friction element 12.

The illustrated friction elements 12 have the cited double-layer structure, which in this case is disposed parallel to the end surface of piezoelectric transducer 9. Layer 37, which is bonded to the surface of piezoelectric transducer 9, is formed as the cited hard but porous member, while layer 38, which comes into contact with friction surface 4 of rotor 1, is made of a hard, abrasion-resistant monolithic material. Aluminum oxide, zirconium oxide or similar materials can be used as the material for the rotor.

In the circuit arrangement according to the practical example for operation of a piezoelectric drive, especially a piezoelectric motor, wherein the drive is constructed as a piezoelectric exciter from a monolithic plate-like piezoelectric transducer with substantially rectangular electrode faces and the electrode faces are disposed on the front and rear sides of the longitudinal sides of the transducer, there is used a primary or

control generator, which is connected directly to a first input of a two-channel bridge power amplifier and, via a phase shifter, indirectly to the second input of the power amplifier. The outputs of the bridge power amplifier are routed via a filter to the primary side of a summing transformer, the secondary side of the transformer being connected on the one hand to the rear electrode and on the other hand, via a changeover switch, to one or the other of the pairs of front-side electrodes. The filter used is an L-C arrangement connected in series.

A first alternative embodiment of the circuit arrangement will be described with reference to Fig. 12. The circuit arrangement, which in Fig. 1 is denoted by 15, comprises a primary or control generator 39 with a frequency-controlling input 40, and a bridge power amplifier 41 with a first channel 42, a second channel 43 and a voltage source V0 (not illustrated).

First channel 42 comprises a driver module 44 and the one half of power amplifier 45 with switch transistors (FET) 51, 52 and output junction 53.

The input of first channel 42 of the power amplifier is connected directly to the output of primary generator 39 and the input of second channel 43 is connected via phase shifter 54 to the output of primary or control generator 39. Furthermore, phase shifter 54 has a control input 55.

The cited summing element of transformer 56 and an L-C serial element as filter 57 are looped into the diagonals of bridge power amplifier 41, or in other words at outputs 48 and 53.

The secondary winding of transformer 54 is connected via changeover switch 58 to one or the other of the electrode groups 10, 11 of piezoelectric transducer 9.



Fig. 13 shows explanatory voltage variation diagrams for an understanding of the motor operation.

Voltage variations  $V_1$  shown in diagrams 59, 62 and 65 occur at output 48 of bridge power amplifier 45. The variations according to diagrams 60, 63 and 66 show the voltages  $V_2$  at output 53 of bridge power amplifier 50. Diagrams 61, 64 and 67 relate to the voltages  $U_{e1}$ ,  $U_{e2}$ ,  $U_{e3}$  at different phase shifts  $\varphi_1$ ,  $\varphi_2$  and  $\varphi_3$  between voltages  $V_1$  and  $V_2$ . The times  $t_1$  and  $t_2$  correspond to the connection times of voltage source  $V_0$  to the primary winding of summing transformer 56 for the first half period  $T_1$  and the second half period  $T_2$ .

The working principle of the part of the circuit arrangement for driving the motor explained in Fig. 12 will be explained with reference to Fig. 14. Diagram 68 shows how the phase-shift angle  $\varphi$  of phase shifter 54 between its input and output signals depends on the voltage  $UV$  at control input 55. Diagram 69 shows the dependence between the phase-shift angle  $\varphi$  and the voltage  $U_e$  at the secondary winding of summing transformer 56.

In the further embodiment of the circuit for operation of a piezoelectric drive according to Fig. 15, there is additionally provided a signal-level transducer 70, a comparator 71 with noninverting input 72 and inverting input 73, and an electronic electrode-group commutator 74.

Input 75 of signal-level transducer 70 is connected to comparator input 76. Output 77 of signal-level transducer 70 is connected to input 55 of phase shifter 54. Comparator outputs 72, 73 are connected to inputs 78, 79 of the electrode-group commutator, the commutating terminals 80, 81 of which are routed to the two electrode groups 10, 11.

Referring now to Fig. 16 and the diagrams shown therein, diagram

82 shows a special dependence of the voltage  $U\varphi$  present at output 77 of signal-level transducer 70 on the voltage  $U_r$  present at output 75. Diagram 83 shows how the phase-shift angle  $\varphi$  at the input and output of phase shifter 54 depends on voltage  $U_r$ . Diagram 84 discloses the dependence of the voltage  $U_k$  at noninverting comparator input 72 on voltage  $U_r$ . The dependence of the velocity of movement of rotor 1 on the voltage  $U_r$  is clearly evident from diagram 85.

According to the diagram of Fig. 17, the possibility exists of disposing on plate-like piezoelectric transducer 9 a bending sensor 86, which detects mechanical bending oscillations of exciter 8.

Sensor 86 is designed as a thin piezoelectric plate with length  $L_s$ , height  $H_s$  and thickness  $D_s$  as plate 87. Diagram 88 shows the sensor in side view.

Electrodes 89 and 90 are disposed on the two main sides of the piezoelectric plate of the sensor. Plate 87 has two parts 90 and 91 of equal length, in which the piezoceramic is polarized in two opposite directions, perpendicular to electrodes 88 and 89. The polarization is indicated symbolically with the arrow diagrams.

The dimensions of plate 87 of sensor 86 are determined by the dimensions of plate-like piezoelectric transducer 9 of the actual exciter. The plate length  $L_s$  should be equal to the width of the transducer, while the width  $H_s$  ranges between 0.02 to 0.2 times the length  $L$ . The thickness  $D_s$  should be minimized to the extent technologically possible. Typically the thickness  $D_s$  ranges between 0.1 and 0.3 mm.

On the surface of plate-like piezoelectric transducer 9, plate 87 of sensor 86 is joined thereto, specifically on lower electrode

(rear-side electrode) 19, where it is disposed midway between the middle node of the bending mode of the oscillations and one of the side nodes, or in other words midway between lines A and B or A and C, such that it runs perpendicular to the longitudinal narrow sides of the piezotransducer.

Sensor 86 can be fastened to the surface of transducer 9 by adhesive bonding using epoxy resin or by soldering with a soft solder.

The operating principle of bending sensor 86 as regards the mechanical bending stresses to be detected is illustrated in Fig. 18. Diagram 92 shows the dependence of the velocity  $V_f$  of movement of rotor 1 on the angular frequency  $\omega$  of primary generator 39. The angular frequency  $\omega_0$  corresponds to the maximum velocity of rotor 1. The dependence of the voltage  $U_s$  present at electrodes 89, 90 of sensor 87 on the angular frequency  $\omega$  of primary generator 39 is shown in diagram 93, while diagrams 94 and 95 symbolize frequency dependences of the phase shift of voltage  $U_s$  and of voltage  $U_e$  at one of the electrode groups.

As shown in the block diagram of Fig. 19, the output signals of bending sensor 86 are linked into the circuit arrangement for control and operation of a piezoelectric drive. In addition, phase detector 96 is provided in this case with phase-support input 97, phase-control input 98 and control-signal output 99.

Electrode 90 of one of the electrode groups 10 or 11 is connected to support-signal generator 100, which comprises a signal limiter 101 as well as a comparator 102. Output 103 of support-signal generator 100 is connected to input 97 of phase detector 96. Electrodes 90, 89 of bending sensor 86 are connected to inputs 104, 105 of control-signal generator 106. The control-signal generator further comprises an isolating transformer 107, a filter 108, a comparator 109 and a control inverter 110 with

control input 111. Output 112 of control-signal generator 106 is connected to control-signal input 98 of phase detector 96.

The operating principle of the circuits described in the foregoing is as follows. Upon startup a voltage is produced whose frequency  $\omega$  is equal to the resonance frequency of the mechanical resonator in the second mode of the bending oscillations of exciter 8. This voltage is supplied via leads 16 to one of the electrode groups 10 or 11 of plate-like piezoelectric transducer 9. Electrode group 10 is formed by the two upper electrodes 17, 18, which are electrically connected to one another, and by lower electrode 19 (see Fig. 2).

Electrode group 11 results from the two upper electrodes 20 and 21, which are electrically connected to one another, and from lower electrode 19. The electric voltage of circuit arrangement 15 is fed either to electrodes 17, 18 and 19 or to electrodes 20, 21 and 19.

Length  $L$  and width  $H$  of plate-like piezoelectric transducer 9 are chosen such that the mechanical resonance frequencies of the second bending mode and of the first longitudinal mode of the oscillations of the exciter are close to one another. Usually the resonance frequency of the longitudinal oscillations is higher by a given amount than the resonance frequency of the bending oscillations, and so an  $L:H$  ratio of approximately 3:7 is chosen for the illustrated example.

By the fact that electrodes 17, 18 and 20, 21 are connected diagonally relative to the longitudinal axis of the plate-like exciter, the action of the applied voltage is unsymmetric. As a result, bending and longitudinal oscillations are simultaneously produced in the exciter. Since the amplitude of these oscillations is small compared with the size of the exciter, these oscillations can be considered independently of one another.

According to diagram 22 in Fig. 2, the bending deformation of exciter 8 leads to a distribution of transverse oscillation velocities  $V_y$  along oscillator length  $L$ . Diagram 23 in Fig. 2 discloses the distribution of longitudinal oscillation velocities  $V_x$  produced by the longitudinal deformations of the exciter. Because of the mutual superposition of oscillations, friction element 12 of exciter 8 performs elliptical movements in the  $x$ - $y$  plane. By means of friction element 12, which is pressed compliantly against the friction surface of the rotor, these elliptical movements are transferred to the rotor, leading to the desired movements thereof.

On the smaller side surfaces of the plate-like transducer, or in other words the longitudinal narrow sides, there are located three nodes of the oscillation velocities  $V_y$  at which the oscillation velocity  $V_y$  is equal to zero. The oscillation nodes in question are located on lines A, B and C (see diagram 23 in Fig. 2). In other words, three points at which no transverse components of the oscillation velocity  $V_y$  exist are located on each of the longitudinal narrow sides of the plate-like piezoelectric transducer. Accordingly, the points denoted by reference symbols 24 in the vicinity of lines B and C are preferably suitable for undertaking fastening of the plate-like piezoelectric transducer from the viewpoint of the static and dynamic loads imposed on the rotor.

The special holding device with double frames, or in other words the fixture for transverse fastening and for pressing, is designed such that it is absolutely elastic in transverse direction  $X$  for the dynamic forces which act with frequency  $\omega_0$  due to the piezoceramic transducer.

For the static force acting along longitudinal axis  $X$ , the fixture functions as an elastic spring, which produces the force necessary to press friction element 12 against friction surface 2

of the rotor. Along axis Y, no dynamic forces are produced by the piezoelectric transducer with frequency  $\omega_0$ , since no components of the oscillation velocity  $V_y$  exist. The holding device is therefore rigid for the forces which act in the transverse direction along the Y-axis.

The structure of the double frames is described in the foregoing with reference to Figs. 1 to 6.

In the functioning condition of the motor, static secondary forces  $F_p$  directed along the X-axis and perpendicular to friction surface 2 of rotor 1 act on housing 6, as illustrated by means of Fig. 7. Under these conditions friction element 12 is braced against friction surface 2, and double frames 13 are pulled apart to small equal distances  $h$ , which are determined by the elasticity of the double frames and by the resultant force  $2F_p$ .

The resultant force  $2F_p$  is chosen such that it is equal to the static force with which friction element 12 is pressed against friction surface 2 of rotor 1. Thereafter housing 6 is fastened to carrier base 4 by means of screws 7. Once the housing has been fixed in this way, force  $2F_p$  is developed due to the elasticity and spring action of double frames 13, whereupon the secondary forces  $2F_p$  can be canceled.

If, for example, the dimensions of the plate-like piezoelectric transducer are  $37 \times 10 \times 3$  mm and of the friction element are  $3 \times 3 \times 4$  mm, the static force  $2F_p$  which presses friction element 12 against friction surface 2 has a magnitude of 10 N. If the double-frame thickness is 0.3 mm and the dimensions of the double frame are substantially  $22 \times 6$  mm, the force of 10 N is developed when the double frame has been pulled apart to a distance  $h = 0.5$  mm.

As is evident from the triangle of forces in diagram 33 of Fig.

8, two static compressive forces  $F_t$ , which act perpendicular to the smaller side surfaces of the plate-like piezotransducer and which are much larger than the actual pressing force  $2F_p$  are developed due to the special double-frame configuration and the action of the static pressing force  $2F_p$ . Such resolution of forces or transformation of forces increases, as explained, the reliability of bonding of the double-frame spring arrangement with piezotransducer 9.

Returning to Figs. 9 and 10, there are illustrated forms of oscillation of double frames 13 which are established due to the bending and longitudinal modes of the oscillations of the exciter. The lateral parts of the outer frames are joined firmly to housing 6 and do not oscillate. The bending modes of the oscillations cause sides 31 of inner frame 26 to turn by a small angle  $\alpha$  around point 0. Under these conditions the oscillations have an amplitude  $\Delta Ab$ . The amplitude  $\Delta Ab$  is small and, for a piezolength of  $L = 37$  mm, amounts to about 0.01 to 0.5  $\mu\text{m}$ . In Fig. 9 the oscillations of the double frames are represented by a dashed line. Inner frames 26 each turn around the stay or the respective bridge 27.

The longitudinal vibration mode leads to transverse shifting of inner-frame sides 31, the oscillation amplitude in this case being about 3 to 6  $\mu\text{m}$  (see Fig. 10). In Fig. 10, the form of oscillation of double frame 13 is also shown clearly by a dashed line. Inner frame 26 and part of outer frame 25 move symmetrically during oscillation, specifically with respect to the fastened sides 29 of outer frame 25.

In both cases mentioned in the foregoing, the oscillations of the transducer cause bending movements of the double frames. The transducer and the double frames joined thereto act as an oscillating system, the frames introducing into the system a small reactive component and almost no active component, since

the frames are made of a material having high mechanical quality. For example, the mechanical quality of heat-treated steel or beryllium bronze exceeds 2000.

Accordingly, the holding device according to the invention simultaneously performs two different functions. In other words, the exciter is fixed in transverse direction and simultaneously the friction element is pressed against the friction surface of the rotor.

By the fact that the piezoelectric motor described in the foregoing has very small internal losses, very high translational velocities of the rotor can be achieved, values greater than 1 to 1.5 m/s being conceivable here.

For transmission of the frictional forces, the inventive friction element has a double structure, in order to ensure a high-quality bond between friction element and piezoceramic surface, and on the other hand in order to achieve adequate long-term stability, especially against abrasion at the friction surface.

To join the friction element having the inventive double structure to the piezoceramic surface, there is used an adhesive that ensures optimal quality of bonding to the ceramic, special types of epoxy resin or low-melting glasses being suggested here. During adhesive bonding of the two-layer friction element, the pores of the porous lower layer are filled with an adhesive, and so the desired secure bond is obtained.

As regards the circuit arrangement, primary or control generator 39 generates a periodic electrical oscillation with a frequency equal to the mechanical resonance frequency  $\omega_0$  of the bending mode. This voltage is present, on the one hand, directly at the input of the first channel of the bridge power amplifier and, on the other hand, at a phase shifter. The output of the phase



shifter is connected to the input of the second channel of the bridge power amplifier. Both channels of the power amplifier have drivers which generate a square-wave voltage at the gate electrodes of the field-effect transistors, and so square-wave symmetric voltages  $V_1$ ,  $V_2$  are always present at the outputs of the half-bridge amplifier. The phase shifter shifts the voltage arriving at its input from primary generator 39 by an angle  $\varphi$ . The angle  $\varphi$  is determined by the control voltage  $U\varphi$  present at the input of the phase shifter. The dependence between the phase shift and the control voltage  $U\varphi$  is illustrated in diagram 68 of Fig. 14. This dependence can also vary as shown by the dashed line.

The control voltage  $U\varphi$  present at the control input of the phase shifter changes the phase shift  $\varphi$  between the voltages  $V_1$  and  $V_2$  present in the branches of the bridge power amplifier. The summing transformer is connected to the output side of the bridge power amplifier.

In the case of change of the phase shift between voltages  $V_1$  and  $V_2$ , changes occur in the times  $t_1$  and  $t_2$  of conduction through the switching transistors of the bridge power amplifier and through the summing transformer, which is connected to  $V_0$  in both voltage directions. Transistors 46 and 52 are open during time  $t_1$ , and transistors 47 and 50 are open during time  $t_2$ . The tappable voltage (outputs 48 and 53) present in the diagonals of bridge power amplifier 41 has square-wave form and has a duration  $t_1$  and  $t_2$  which depends on the angle  $\varphi$ . During the times ( $T_1-t_1$  and  $T_2-t_2$ ), outputs 48 and 53 of the bridge power amplifier are connected, in the first case via transistors 47 and 52, and in the second case via transistors 46 and 52.

Because of LC band-pass filter 57 connected in series with the primary winding of the summing transformer, practically only the current of the first harmonic of the voltage present at outputs

48 and 53 flows through the transformer. As a result, the voltage  $U_e$  present at the secondary winding of the summing transformer has a sinusoidal variation. The amplitude of this voltage ( $U_{e1}$ ,  $U_{e2}$ ,  $U_{e3}$ ) depends on the duration  $t_1$  and  $t_2$  and also has a dependence on the phase shift  $\varphi$  ( $\varphi_1$ ,  $\varphi_2$ ,  $\varphi_3$ ) between the voltages  $V_1$  and  $V_2$ . This dependence is illustrated in diagram 69 of Fig. 14.

The phase-shift angle  $\varphi$  changes due to the changed control voltage  $U_\varphi$  present at input 55 of phase shifter 54. Hereby the voltage  $U_e$  at the secondary winding of the summing transformer also depends on the voltage  $U_\varphi$ . The voltage  $U_e$  excites the piezoelectric transducer. The amplitude of the voltage  $U_e$  then determines the amplitude of oscillation of the transducer. During changes of the voltage  $U_\varphi$ , the velocity of rotor 1 also changes.

The piezoelectric motor that can be activated with the described circuit arrangement therefore permits control of the rotor velocity by changing the control voltage  $U_\varphi$  present at the control input of the phase shifter. Motor control can then be achieved almost without energy loss, since the output transistors of power amplifier 41 are always in switched mode of operation.

The voltage  $U_e$  is applied to electrode groups 10 or 11, changeover being possible by means of the corresponding switch 58. The direction of movement of the rotor can be changed by changeover.

As explained by means of Fig. 15, it is possible in one embodiment of the control circuit to predetermine the rotor velocity and direction by unipolar control voltages  $U_r$ . For this purpose there are additionally provided the signal-level transducer, comparator and electrode-group commutator.

At a control voltage of  $0.5 U_r$ , the rotor is in braked condition,

whereas, at a voltage in the region of 0 or  $U_r$ , movement with maximum velocity takes place. The dependence of the output voltage of the signal-level transducer on the input voltage  $U_r$  is shown with diagram 28 of Fig. 16. During an increase of control voltage  $U_r$ , the output voltage  $U_\phi$  also increases linearly, reaching the maximum value at a voltage of  $0.5 U_r$ . With further increase of the voltage  $U_r$ , the voltage  $U_\phi$  decreases linearly. Since the voltage  $U_\phi$  reaches the control input of the phase shifter, the increase of  $U_r$  first of all leads to reduction of the phase-shift angle and then to an increase thereof, as is clearly illustrated in diagram 83 of Fig. 16.

Between the voltage values  $0.5 U_r$  and 0, the comparator is in a first state. The logical value 1 is then present at its noninverting output 72 and the logical value 0 at inverting output 73. In such a state of comparator 71, output 80 of the electronic commutator is closed and output 81 is open, while the rotor is moving with velocity  $V_f$ . The point  $0.5 U_r$  is the point of reversal of the movement of the rotor. Upon passage through this point  $0.5 U_r$ , comparator 71 changes over, leading to inversion of the signals at outputs 72 and 73 and at inputs 78 and 79 of electrode-group commutator 74. The latter leads to a change of state of commutator 74. Its output 80 is now opened and output 82 is closed. Herewith the rotor now changes its direction of movement. A further decrease of the voltage  $U_r$  causes an increase of the phase-shift angle  $\phi$  and an increase of the velocity  $V_f$  of the rotor.

During operation of piezoelectric motors in a broad temperature range, a temperature-induced shift of the mechanical resonance frequency takes place. This effect becomes more pronounced the greater the oscillator quality is, or in other words the smaller its mechanical losses are. The temperature shift of the resonance frequency prevents stable motor operation. In order to avoid this effect, in an embodiment of the motor that has been explained,

the exciter frequency of the primary generator follows the temperature changes of the resonance frequency of the bending oscillation mode of the piezoelectric exciter. In this case the mechanical bending component of the stresses is determined by means of a bending sensor, and a corresponding sensor signal is derived and supplied to a feedback branch.

The flat plate-like structure of the sensor with bidirectional polarization makes it possible to select a component of an electrical voltage  $U_s$  that is proportional to the component of the mechanical exciter, and which in turn is proportional to the velocity of oscillation of the bending mode of the exciter.

The bending deflection or deformation of the plate-like transducer along the X-axis in the XY plane leads to compression of one half of bending-sensor plate 87 and to pulling apart of the other half 90 or 91 of sensor 86. In such a sensor construction, the stresses produced by each plate half 90 and 91 are equally large and unipolar as well as proportional to the mechanical exciter stresses. The longitudinal deformation of plate 87 as a consequence of the longitudinal oscillation mode acting on sensor 86 leads to compression and pulling apart of halves 90 and 91, and so equal stresses of opposite sign are produced that compensate for one another.

The dependence of the rotor velocity  $V_f$  and of the voltage amplitude  $U_s$  at electrodes 89 and 90 of sensor 86 on the exciter frequency  $\omega$  is illustrated in diagrams 92 and 93 of Fig. 18. These dependences mirror one another, and the velocity maximum  $V_f$  corresponds to the voltage maximum  $U_s$ . Both maxima are located at the point of the mechanical resonance frequency of the bending oscillation mode  $\omega_0$ .

Diagrams 94 and 95 illustrate how the phase-shift angle  $\varphi_f$  depends on the exciter voltage  $U_e$  at one electrode group, and on

the other hand show the voltage  $U_f$  established at electrodes 89 and 90 of sensor 86. The phase-shift angle  $\varphi_s = 90^\circ$  corresponds to the maximum value of the movement velocity  $V_s$ . When the electrode groups are changed over from group 10 to group 11, the phase-shift angle  $\varphi_s$  changes to  $180^\circ$ , or in other words to  $-90^\circ$ . The dependence of phase-shift angle  $\varphi_s$  on exciter frequency  $\omega$  illustrated in diagram 95 of Fig. 18 extends over a broad temperature range, and this dependence is used as a form of feedback in order to correct the primary generator as a function of temperature changes and of the changed resonance frequency.

The feedback branch necessary for this purpose includes sensor 86 and phase detector 96. The additionally present phase detector generates an error signal that is proportional to the phase difference  $\varphi_f$  between the voltages at its support input 97 and at the control input 98 relative to a value of  $90^\circ$  or any other predesignated value.

The error signal is relayed by output 99 to control input 40 of primary generator 39, whereby its exciter frequency is changed such that the phase difference always remains equal to a predesignated value  $\varphi_s$ .

The voltage  $U_e$  at one of the electrode groups 10 or 11 is used as the support signal. This voltage is limited by limiter 101 and reshaped by comparator 102. In this case the control signal is the voltage  $U_s$  present at sensor electrodes 89 and 90. The voltage  $U_s$  is first delivered to isolating transformer 107, after which the first harmonic is filtered out by means of a filter 108 and the signal is reshaped to square-wave form via comparator 109. Comparator 109 is connected to controlled inverter 110, whose control input is connected to one of the comparator outputs 72 or 73. Controlled inverter 110 rotates the phase of the control signal by  $180^\circ$  depending on whether electrode group 10 or 11 is selected. Thereafter the signal is relayed by output 112 of

inverter 110 to control input 98 of phase detector 96.

With the circuit described in the foregoing, the resonance frequency of the primary generator can be kept equal to the mechanical resonance frequency of the exciter over a broad temperature range, and so motor operation with high precision can be achieved almost independently of temperature.

The presented piezoelectric drive, especially piezoelectric motor, has low mechanical losses due to the special holding device by means of double frames. The losses can be estimated by the effective quality of the unloaded exciter, or in other words in the absence of contact with the rotor in the operating situation. The measured quality of the unloaded exciter ranges between 500 and 700. Accordingly, typical effective values approximately ten times better than those of known motors can be achieved. In the proposed solution, the connecting points between the piezoelectric transducer and the holding device practically do not heat up, and so no additional exciter heating takes place. This also contributes to improved and stable motor operation. The motor therefore has a more favorable energy balance and greater efficiency. The exciter voltage can be as much as three times smaller than in known solutions. Likewise the positioning precision is high, extending into the range of several nanometers, which represents an inherently theoretical limit.

## Reference symbols

- 1 Rotor
- 2 Friction surface
- 3 Bearing
- 4 Base or carrier
- 5 Drive element
- 6 Housing of the drive element
- 7 Fastening screws of the housing
- 8 Piezoexciter
- 9 Plate-like piezoelectric transducer
- 10, 11 Electrode group
- 12 Friction element
- 13 Flat, elastic double frames
- 14 Fastening screws of the double frame
- 15 Driver arrangement for the piezoelectric transducer
- 16 Lead wires
- 17, 18 Upper electrode
- 19 Lower electrode
- 20, 21 Upper electrode
- 22 Diagram with illustration of the velocities of oscillation of the bending-oscillation mode
- 23 Diagram of the velocities of oscillation of the longitudinal-oscillation mode
- 24 Fastening points of the flat elastic double frame
- 25 Outer frame
- 26 Inner frame
- 27 Stay or bridge or middle bridging structure between inner and outer frame
- 28 Air gap
- 29 Side of the outer frame
- 30 Fastening bores in the outer frame
- 31 Side of the inner frame
- 32 Adhesive or solder drop
- 33 Triangle of forces
- 34 - 36 Alternative versions of the friction element
- 37 Porous layer part

38	Monolithic friction-layer part
39	Primary generator
40	Control input of the primary generator
41	Two-channel bridge power amplifier
42	First channel of the bridge power amplifier
43	Second channel of the bridge power amplifier
44	Driver of the first channel
45	Half-bridge of the power amplifier
46	Upper transistor of the power amplifier
47	Lower transistor of the power amplifier
48	Output of the power amplifier
49	Driver of the second channel of the power amplifier
50	Half-bridge of the power amplifier
51	Upper transistor of the power amplifier
52	Lower transistor of the power amplifier
53	Output of the power amplifier
54	Phase shifter
55	Control input of the phase shifter
56	Summing transformer
57	Filter
58	Electrode-group changeover switch
59 - 67	Voltage diagrams
68, 69	Explanatory diagrams relating to the working principle of the circuit arrangement
70	Signal-level transducer
71	Comparator
72	Noninverting comparator output
73	Inverting comparator output
74	Electric electrode-group commutator
75	Control input of the signal-level transducer
76	Comparator output
77	Output of the signal-level transducer
78, 79	Control inputs of the electronic commutator
80, 81	Outputs of the electronic electrode-group commutator
82 - 85	Explanatory diagrams on the principle of action of the circuit arrangement
86	Bending sensor



- 87 Piezoelectric sensor plate of the bending sensor
- 88 Diagram of the piezoelectric plate of the bending sensor
- 89, 90 Electrodes of the bending sensor
- 91 Portion of the bending sensor
- 92 - 95 Explanations of the action of the bending sensor
- 96 Phase detector
- 97 Support-signal input of the phase detector
- 98 Control input of the phase detector
- 99 Phase-detector input
- 100 Support-signal generator
- 101 Signal limiter
- 102 Comparator
- 103 Output of support-signal generator 100
- 104, 105 Inputs of the control-signal generator
- 106 Control-signal generator
- 107 Isolating transformer
- 108 Filter
- 109 Comparator
- 110 Controlled inverter
- 111 Control input of the inverter
- 112 Output of the inverter

## Claims

1. A piezoelectric drive, especially a piezoelectric motor for producing continuous or stepwise movements, comprising a rotor provided with a friction surface, a drive element in the form of a piezoelectric exciter that can be brought into contact with this surface, the exciter comprising a monolithic, plate-like, piezoelectric transducer provided with substantially rectangular electrode faces, an outer fastening, a friction element disposed on one of the end faces of the piezoelectric transducer, as well as a holding device for the piezoelectric transducer and means for pressing the friction element elastically against the friction surface, characterized in that an elastic double frame enclosing the transducer and having inner and outer frames is disposed at each outer node of the bending oscillation mode for the purpose of holding the piezoelectric transducer and for producing the pressing force of the friction element, the inner frame being joined to each of the longitudinal narrow sides of the transducer and the outer frame to the outer fastening, and furthermore the outer frame and inner frame being spaced apart and maintained in contact via stays or bridges.
2. A piezoelectric drive according to claim 1, characterized in that the double frame has a structure that is symmetric along its axis, and the centrally disposed stays or bridges join inner and outer frames.
3. A piezoelectric drive according to claim 1 or 2, characterized in that two oppositely disposed stays or bridges are provided, and in that a spacing gap is formed between the longitudinal broad sides of the transducer and the inner frame.

4. A piezoelectric drive according to one of the preceding claims,  
characterized in that  
the double frame is made of a high-quality metal material.

5. A piezoelectric drive according to one of the preceding claims,  
characterized in that  
the inner frames are each fastened by continuous material to the transducer.

6. A friction element for a piezoelectric drive for transmission of forces between stator and rotor, the piezoelectric exciter comprising a monolithic, plate-like, piezoelectric transducer provided with substantially rectangular electrode faces and the friction element being fastened to an end face of the transducer, characterized in that  
the friction element is provided with a double-layer structure, wherein the part of the layer structure bonded to the transducer is formed as a hard, porous member and the part of the layer structure maintained in contact with the rotor is formed as an abrasion-resistant monolithic member, the two layers or members being bonded by sintering.

7. A friction element according to claim 6,  
characterized in that  
fillers to achieve a firm bond between the transducer surface and the friction element are disposed in or introduced into the pores of the part of the layer structure bonded to the transducer.

8. A friction element according to claim 7,  
characterized in that  
the filler is epoxy resin and/or low-melting glass.

9. A friction element according to one of claims 6 to 8, characterized in that the interface of the double-layer structure is oriented substantially parallel to the end face of the transducer.

10. A friction element according to one of claims 6 to 9, characterized by the use thereof for a drive according to the features of at least one of claims 1 to 5.

11. A circuit arrangement for operating a piezoelectric drive, especially a piezoelectric motor, wherein the drive is constructed as a piezoelectric exciter comprising a monolithic, plate-like, piezoelectric transducer provided with substantially rectangular electrode faces, the electrode faces are disposed on the front and back sides of the longitudinal broad sides of the transducer and the front sides of the electrodes are divided into four quadrants and are also interconnected diagonally in pairs, characterized in that a primary or control generator is connected directly to a first input of a two-channel bridge power amplifier and via a phase shifter to the second input of the power amplifier, the outputs of the bridge power amplifier being routed via a filter to the primary side of a summing transformer and the secondary side of the transformer being connected on the one hand to the rear-side electrode and on the other hand, via a changeover switch, to one or other of the pair of front-side electrodes.

12. A circuit arrangement according to claim 11, characterized in that the filter is an L-C arrangement connected in series.

13. A circuit arrangement according to claim 11, characterized in that the filter comprises an L-C arrangement on the primary and/or secondary side of the transformer and a signal-level transducer

is provided whose output is routed to the control input of the phase shifter and whose input is connected via a comparator to an electrode-group comparator, the electrode-group comparator being connected respectively to the inverting and to the noninverting comparator output.

14. A circuit arrangement according to one of claims 11 to 13, characterized in that a bending sensor for determination of mechanical strictions is disposed on the piezoelectric transducer, the bending-sensor electrodes being connected via a signal-evaluation unit to a control input of the primary generator.

15. A circuit arrangement according to claim 14, characterized in that the signal-evaluation unit comprises a phase detector with phase-support input, the control-signal output of the phase detector being routed to the primary generator for the purpose of changing the exciter frequency, in order to control it to a constant, predetermined phase difference even during fluctuations of the temperature of the piezoelectric transducer.

16. A circuit arrangement according to claim 14 or 15, characterized in that the bending sensor for determination of the bending components of the mechanical excitation is constructed as a thin, single-layer piezoceramic plate with electrodes covering the entire main surface and is polarized symmetrically relative to the transverse axis, the bending sensor being rigidly joined to one of the transducer surfaces between middle and side nodes of the bending mode of the oscillations.

17. A circuit arrangement according to one of claims 11 to 16, characterized by the use thereof for activation of a piezoelectric drive according to one of claims 1 to 5.

## Abstract

The invention relates to a piezoelectric drive, especially a piezoelectric motor for producing continuous or stepwise movements, to a friction element for such a piezoelectric drive as well as for transmission of forces between stator and rotor, as well as to a circuit arrangement for operating a piezoelectric drive, especially a piezoelectric motor.

An elastic double frame enclosing the transducer and having inner and outer frames is disposed at each outer node of the bending oscillation mode for the purpose of holding the piezoelectric transducer and for producing the pressing force of the friction element, the inner frame being joined to each of the longitudinal narrow sides of the transducer and the outer frame to the outer fastening, and furthermore the outer frame and inner frame being spaced apart and maintained in contact via stays or bridges. The inventive friction element is constructed as a double-layer structure with a first hard, porous member joined to the transducer and with a second part or member comprising an abrasion-resistant monolithic material maintained in contact with the rotor, the two layers being bonded by sintering. The circuit arrangement for operation of the drive relies on a special bridge power amplifier as well as on the capability of compensating for the temperature variation of the drive for the purpose of stable operation thereof.

1/16

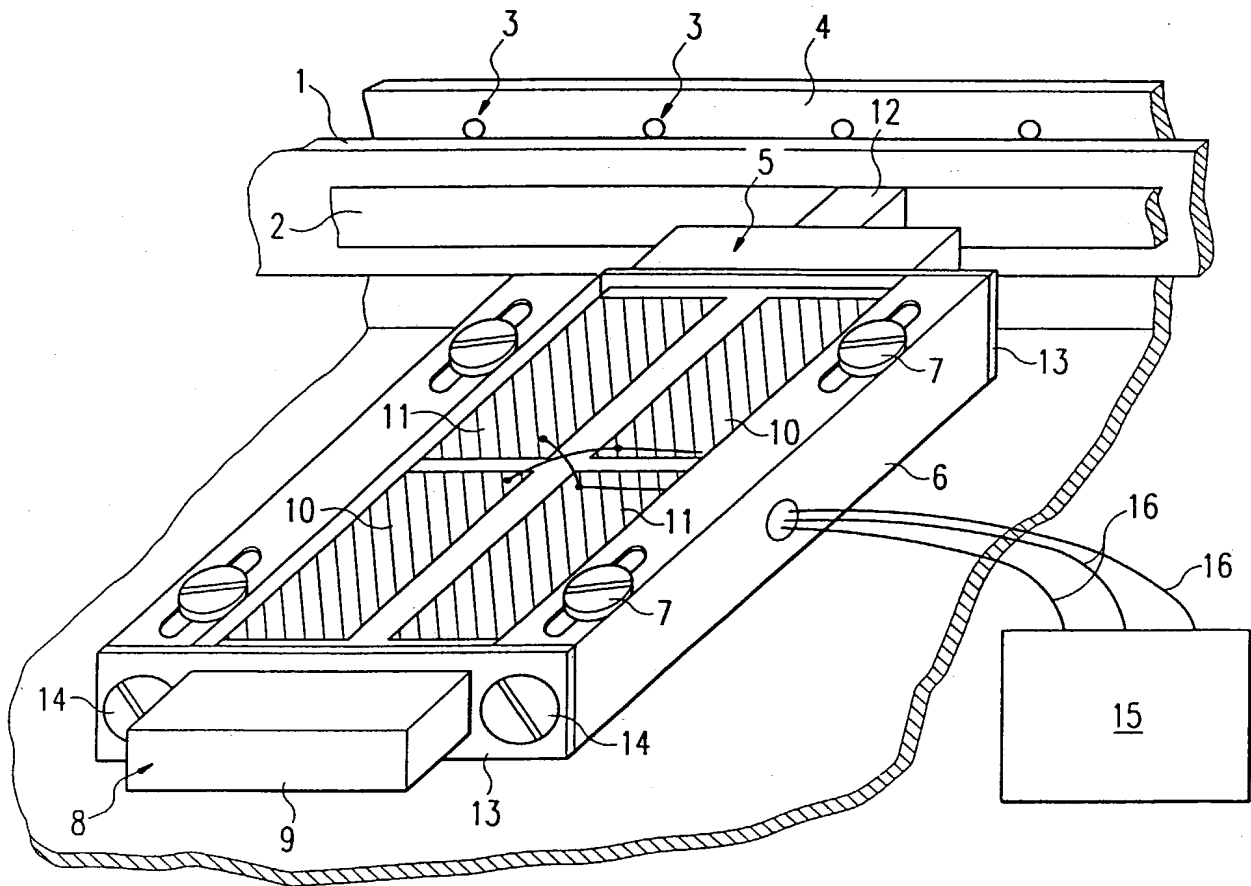


Fig. 1

2/16

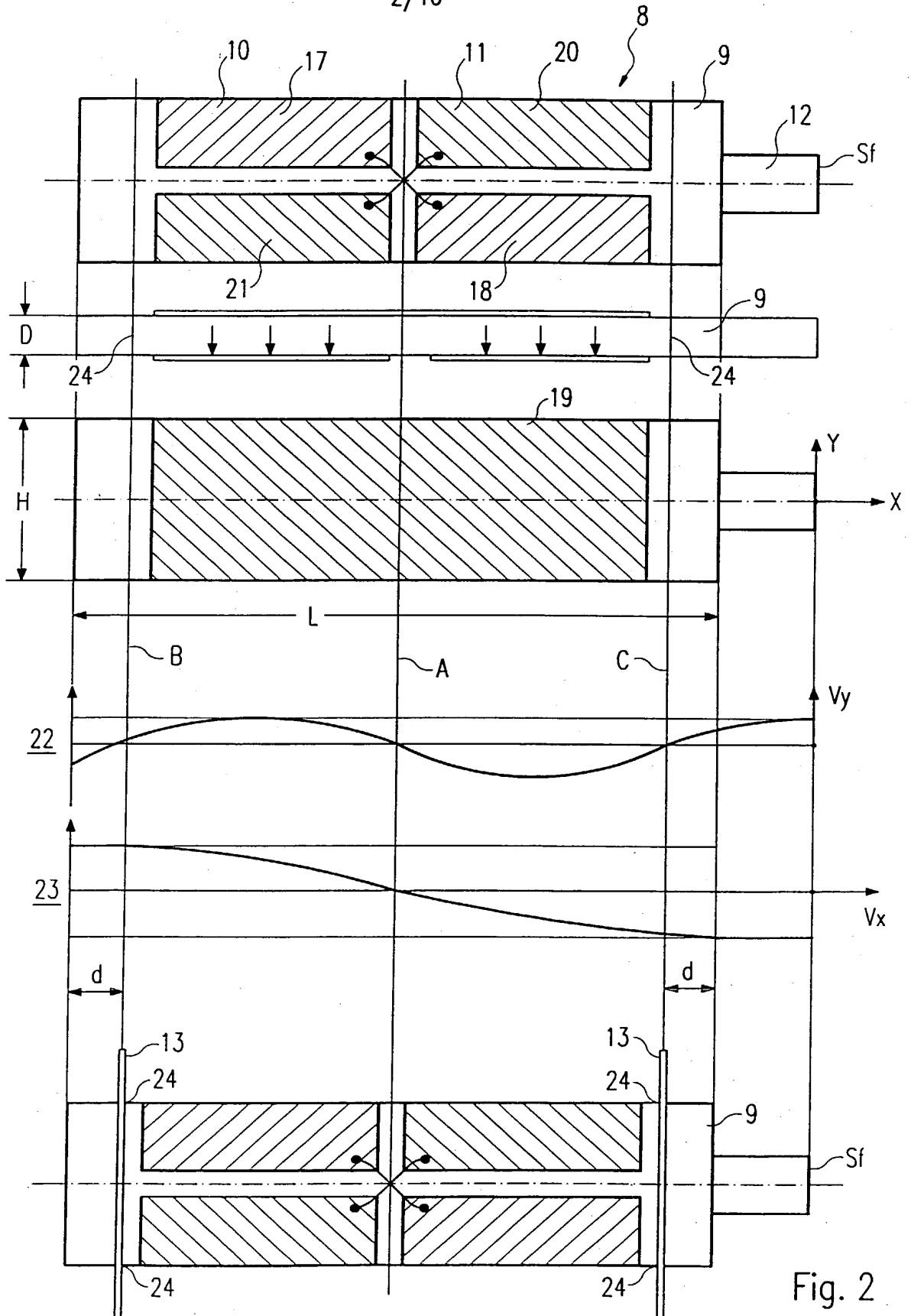


Fig. 2



3/16

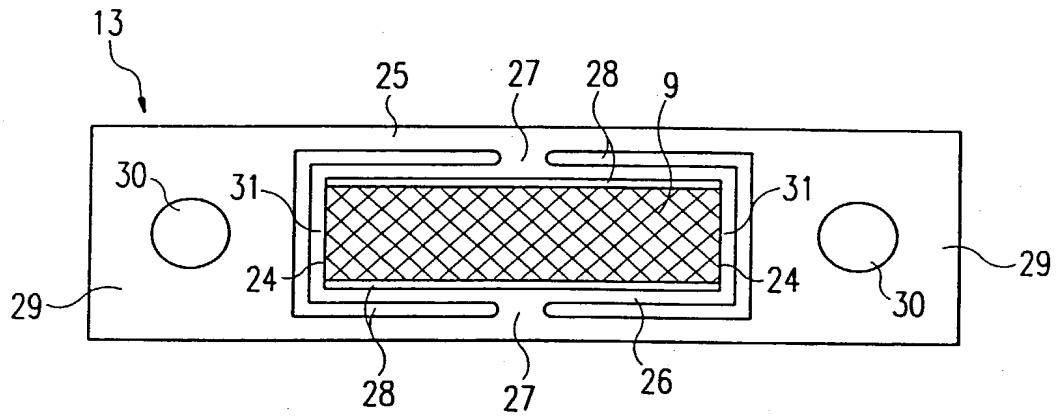


Fig. 3

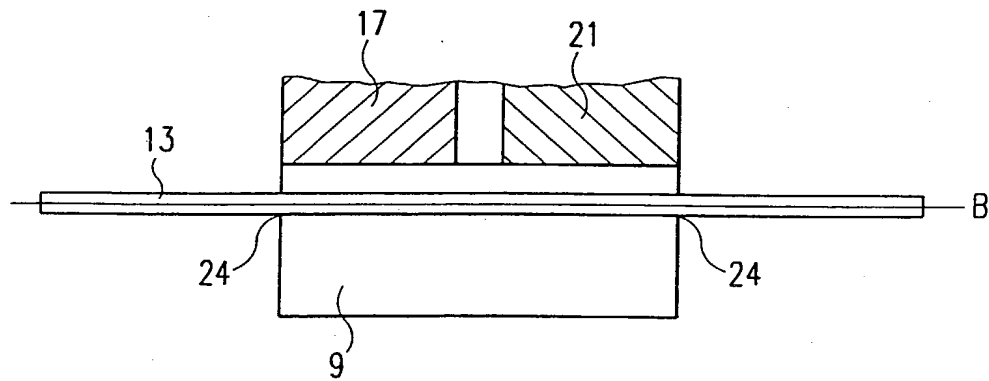


Fig. 4

4/16

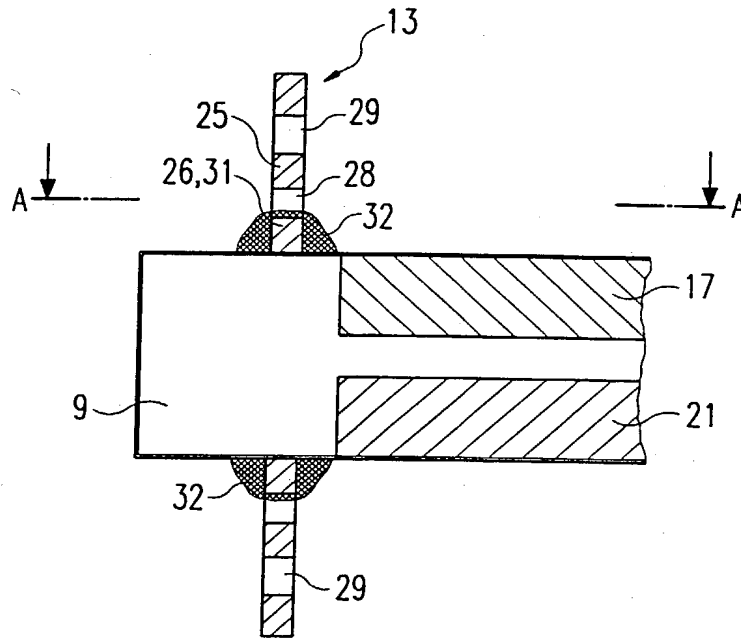


Fig. 5

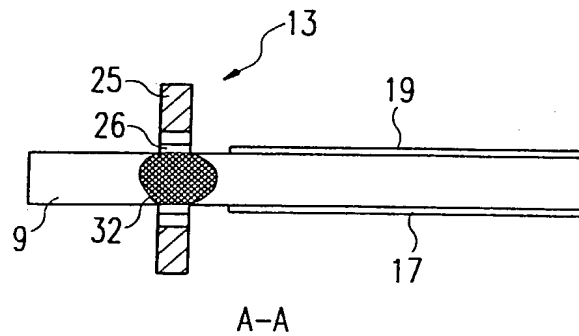


Fig. 6

5/16

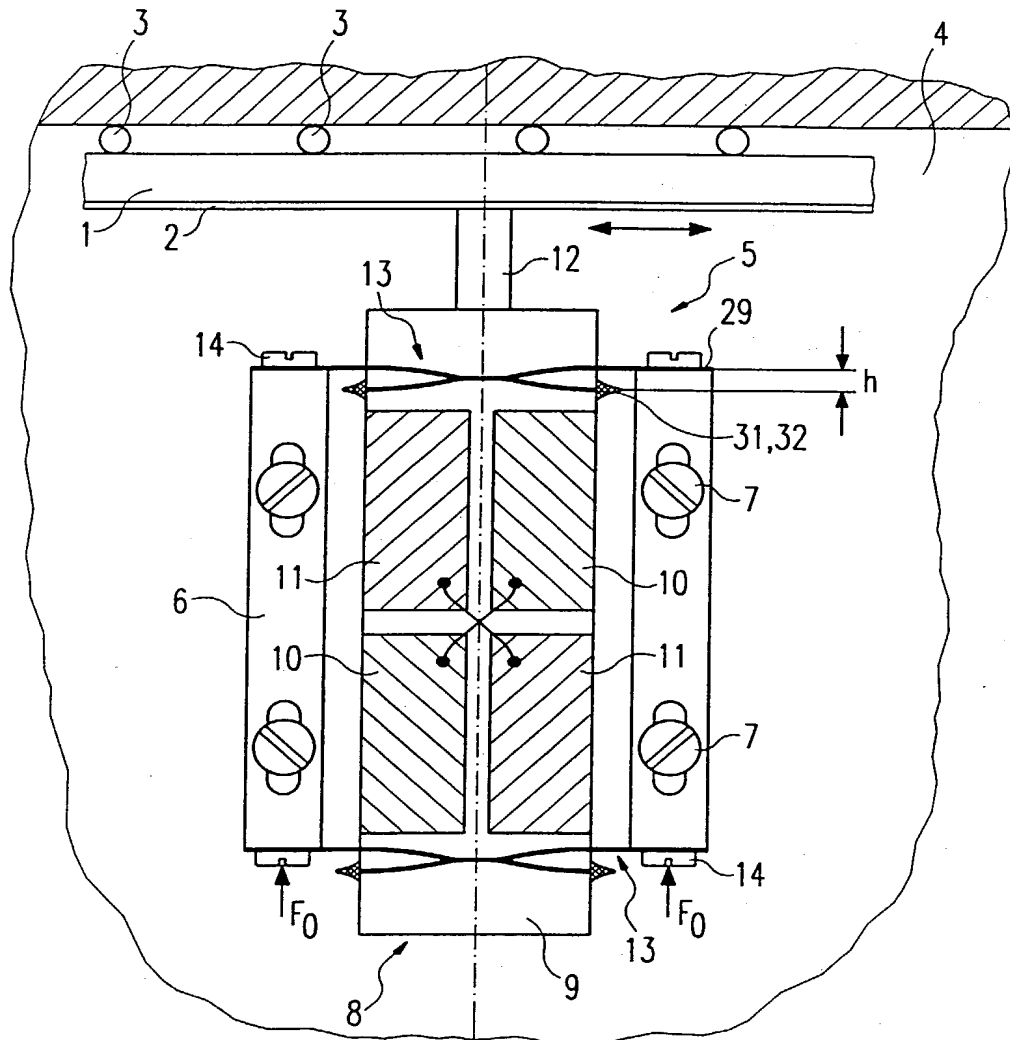


Fig. 7

6/16

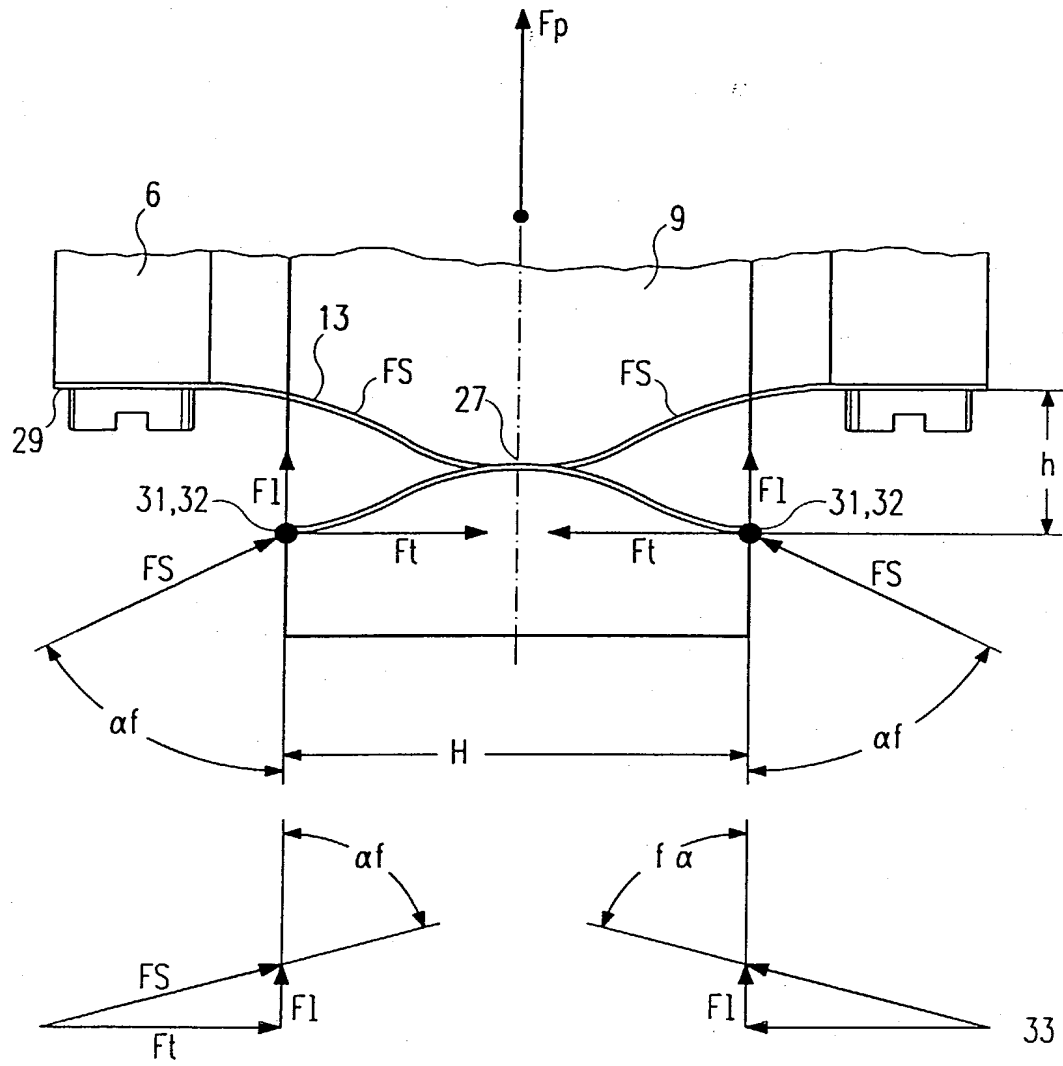


Fig. 8

7/16

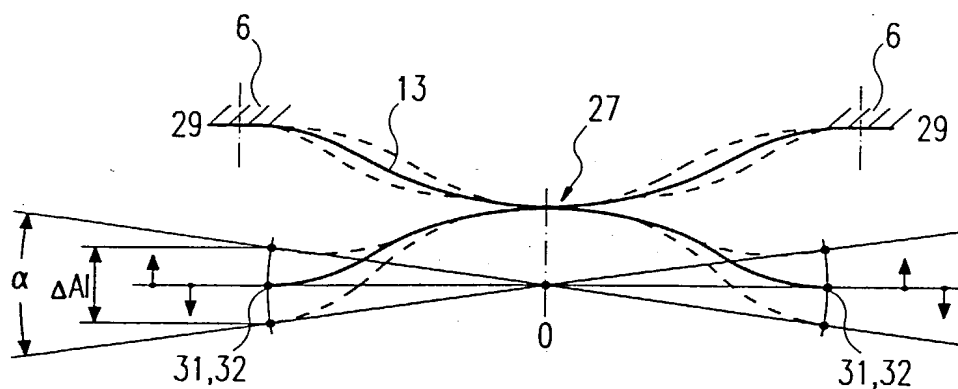


Fig. 9

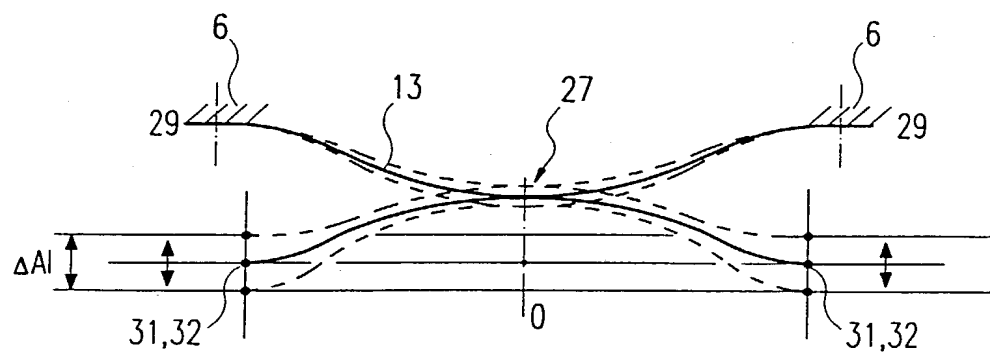


Fig. 10

8/16

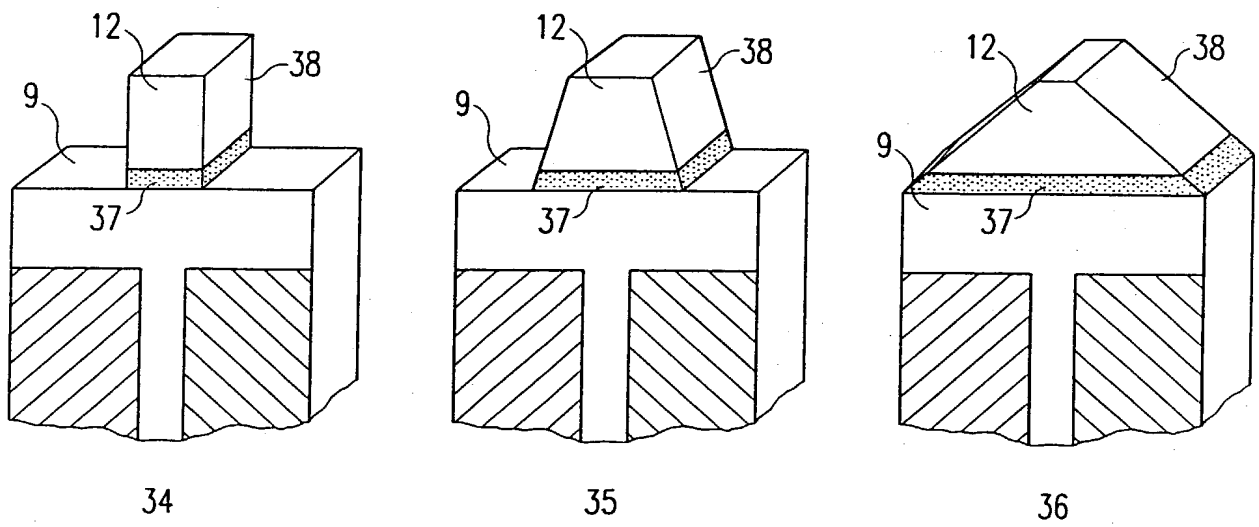


Fig. 11

9/16

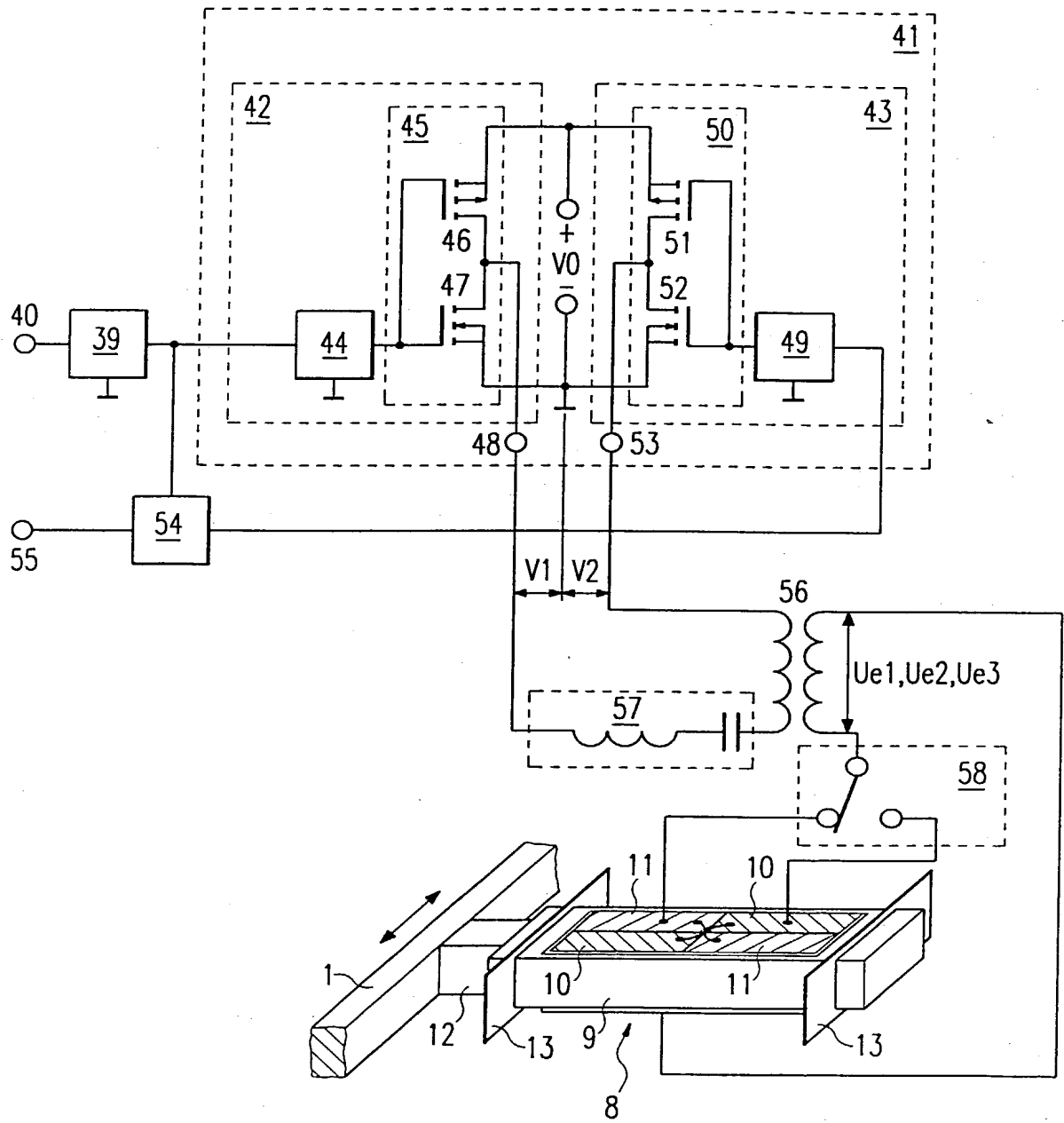


Fig. 12

10/16

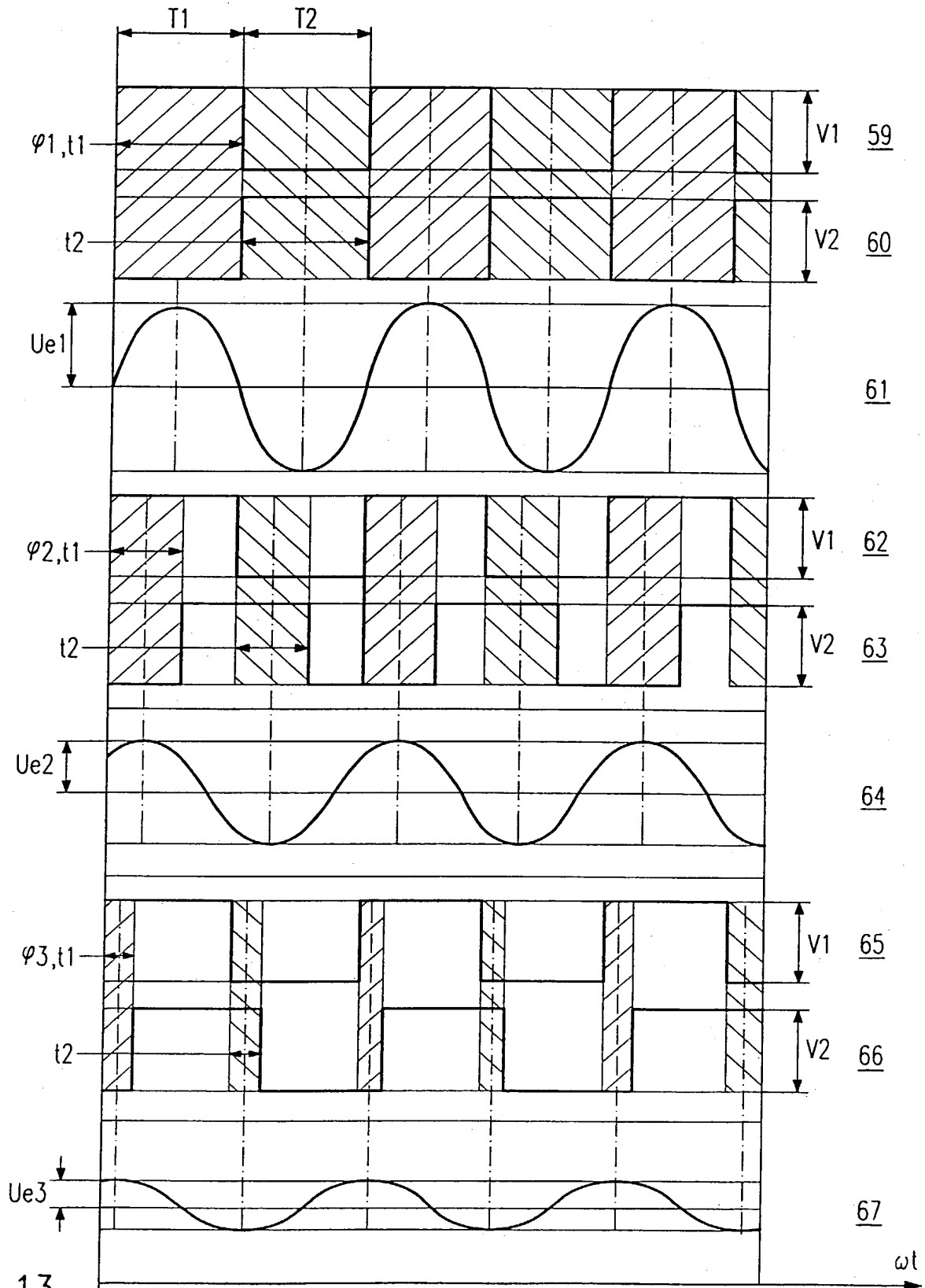


Fig. 13



11/16

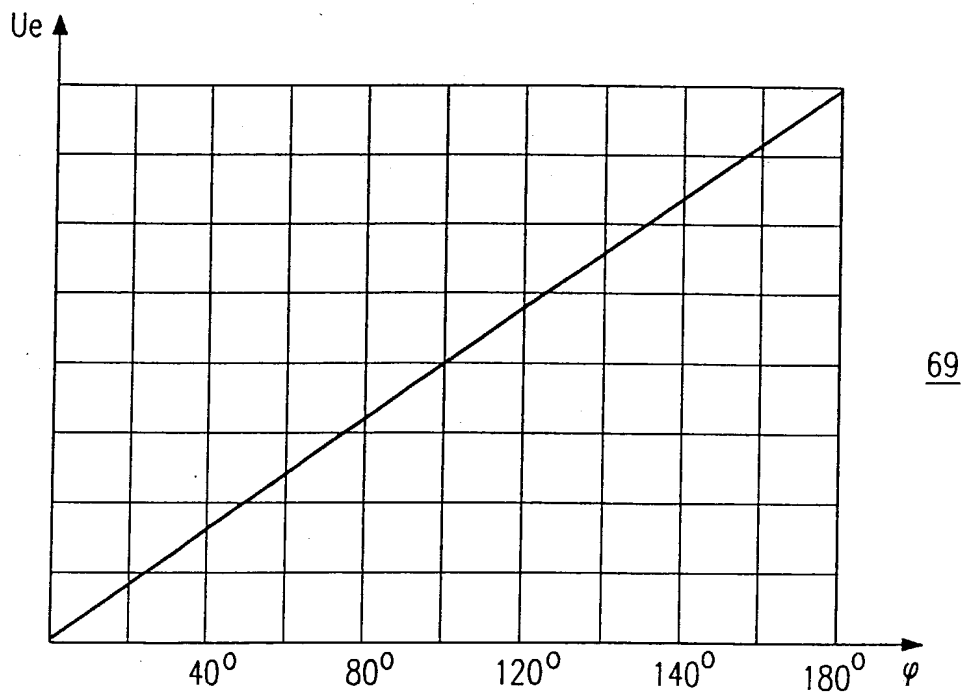
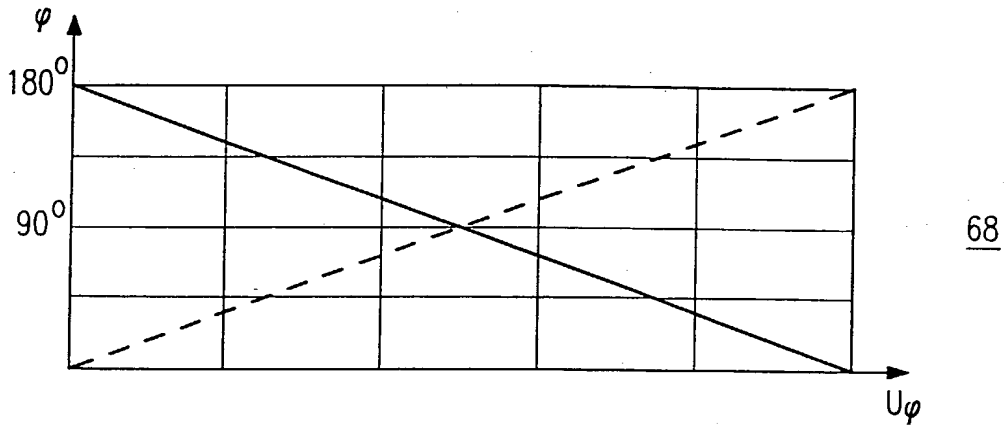


Fig. 14

12/16

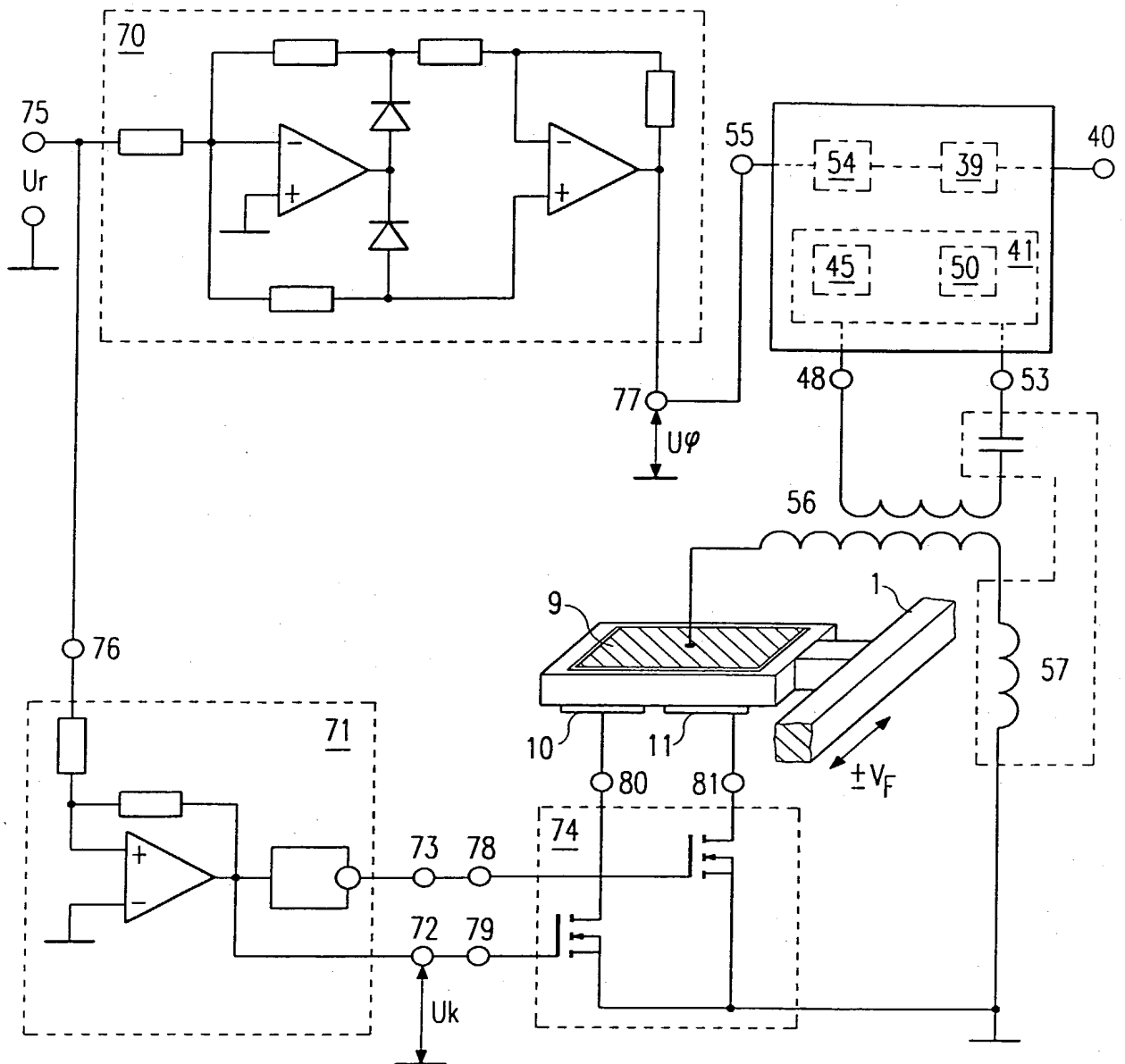


Fig. 15

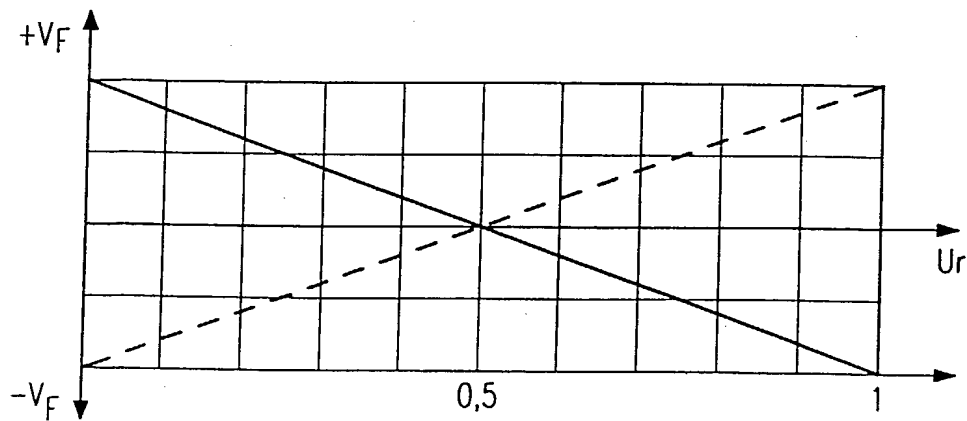
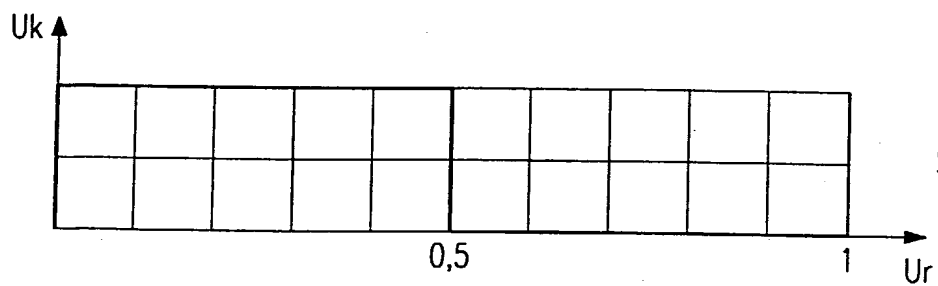
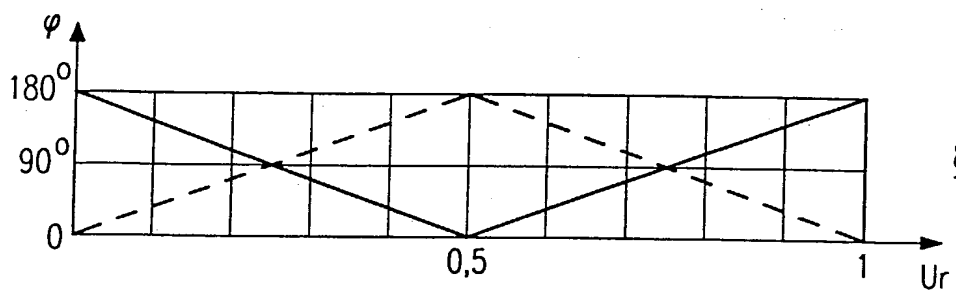
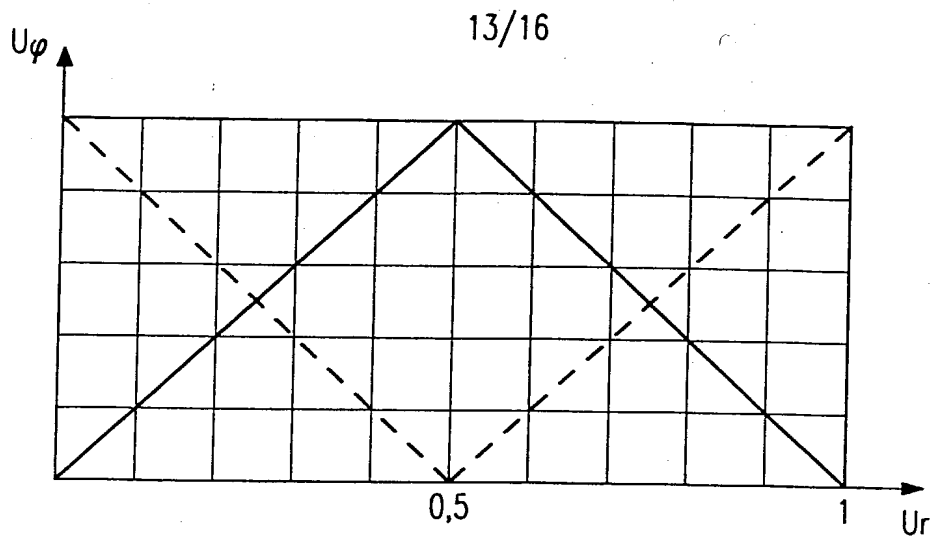


Fig. 16

14/16

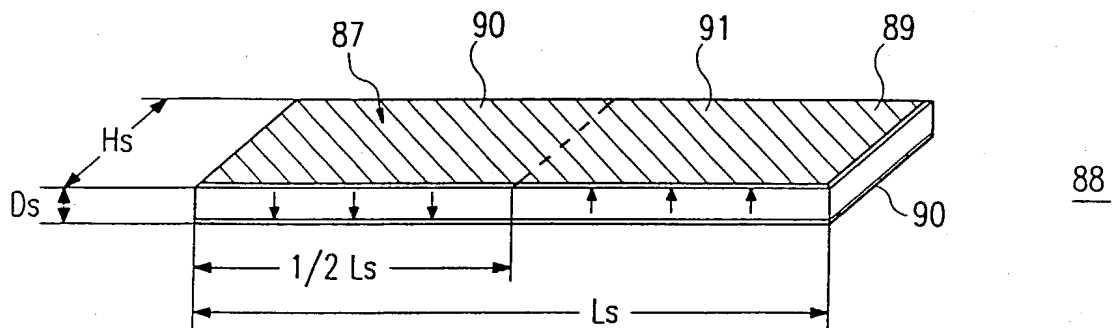
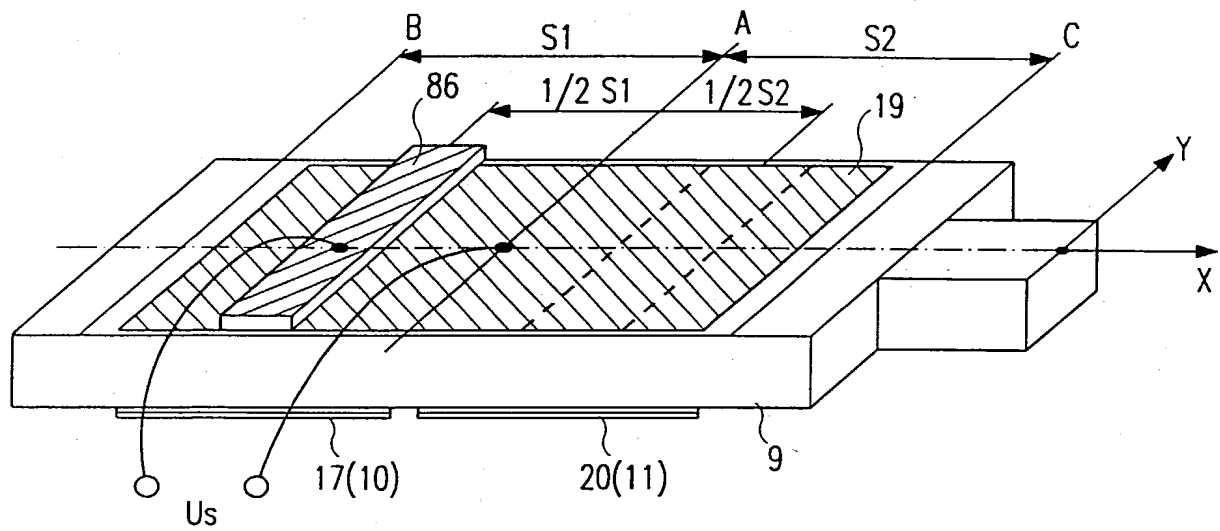
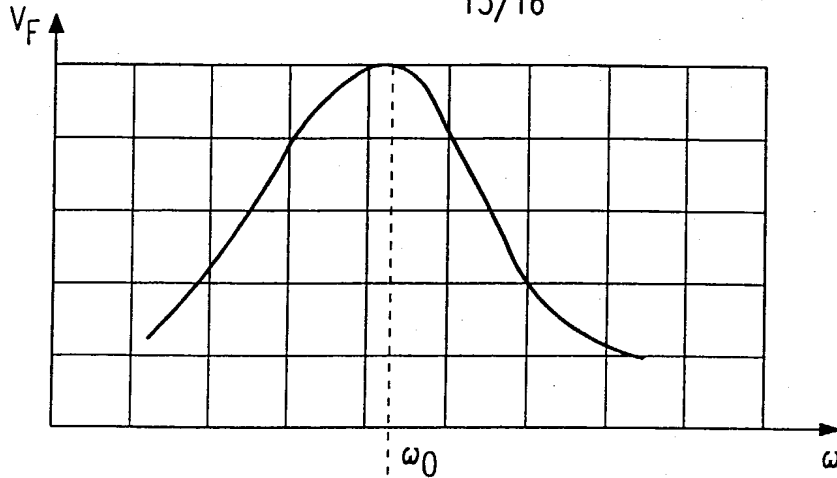
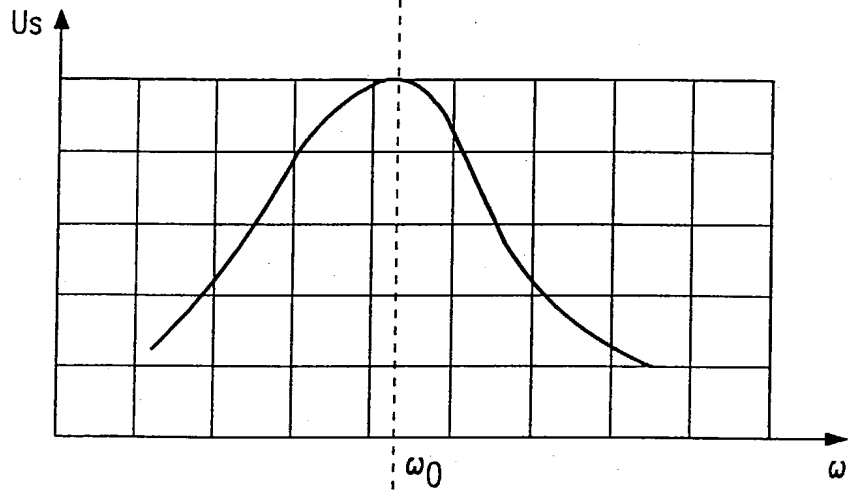


Fig. 17

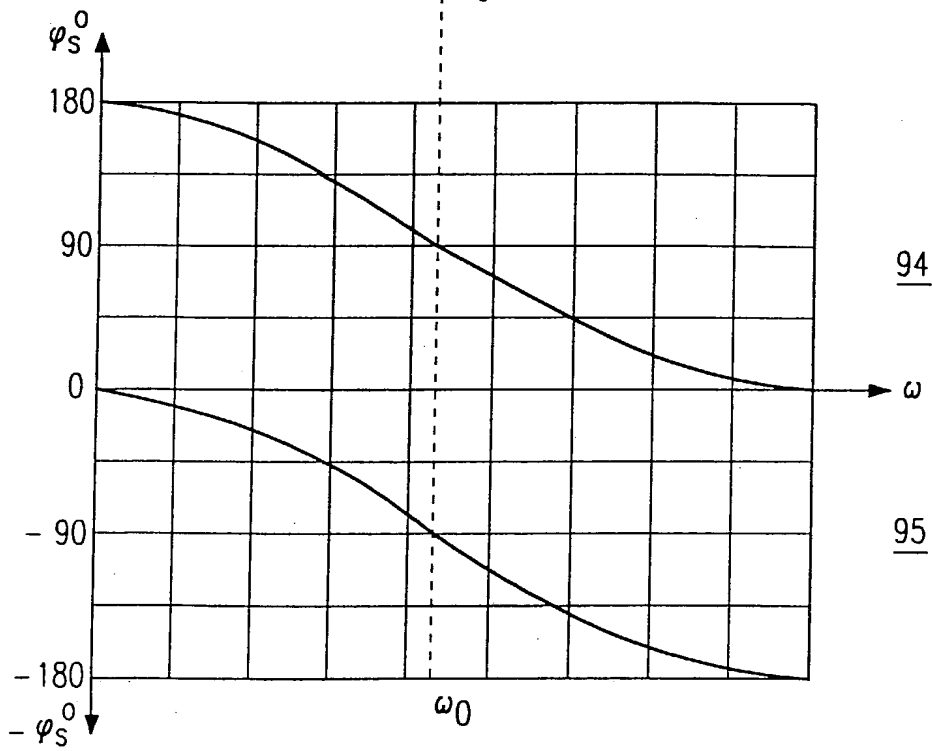
15/16



92



93



94

$-\phi_S^0$

95

Fig. 18

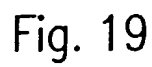


Fig. 19

# Declaration and Power of Attorney for Patent Application

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### German Language Declaration

Als nachstehend benannter Erfinder erkläre ich hiermit an  
Eides Statt:

daß mein Wohnsitz, meine Postanschrift und meine Staatsangehörigkeit den im nachstehenden nach meinem Namen aufgeführten Angaben entsprechen, daß ich nach bestem Wissen der ursprüngliche, erste und alleinige Erfinder (falls nachstehend nur ein Name angegeben ist) oder ein ursprünglicher, erster und Miterfinder (falls nachstehend mehrere Namen aufgeführt sind) des Gegenstandes bin, für den dieser Antrag gestellt wird und für den ein Patent für die Erfindung mit folgendem Titel beantragt wird:

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As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

PIEZOELECTRIC DRIVE, ESPECIALLY A

HOLDING FRAME, A FRICTION ELEMENT AND A

CIRCUIT CONFIGURATION (as amended)

the specification of which:

☐ is attached hereto.

☒ was filed on June 30, 2000

as United States Application Number or PCT International Application Number

PCT/EP00/06133 and was amended on

\_\_\_\_\_ (if applicable).

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, § 1.56.

## German Language Declaration

Ich beanspruche hiermit ausländische Prioritätsvorteile gemäß Title 35, US-Code, § 119(a)-(d), bzw. § 365(b) aller unten aufgeführten Auslandsanmeldungen für Patente oder Erfinderurkunden, oder § 365(a) aller PCT internationalen Anmeldungen, welche wenigstens ein Land ausser den Vereinigten Staaten von Amerika benennen, und habe nachstehend durch ankreuzen sämtliche Auslandsanmeldungen für Patente bzw. Erfinderurkunden oder PCT internationale Anmeldungen angegeben, deren Anmeldetag dem der Anmeldung, für welche Priorität beansprucht wird, vorangeht.

I hereby claim foreign priority under Title 35, United States Code, § 119(a)-(d) or § 365(b) of any foreign application(s) for patent or inventor's certificate, or § 365(a) of any PCT International application which designated at least one country other than the United States, listed below, and have also identified below, by checking the box, any foreign application for patent or inventor's certificate, or PCT International application having a filing date before that of the application on which priority is claimed.

Prior foreign application(s)  
(Frühere ausländische Anmeldungen)

Priority claimed

Priorität  
beansprucht

199 45 042.0      Germany  
\_\_\_\_\_  
(Number)      (Country)  
(Number)      (Land)

\_\_\_\_\_  
(Number)      (Country)  
(Number)      (Land)

30 June 1999  
\_\_\_\_\_  
(Day/Month/Year Filed)  
(Tag/Monat/Jahr der Anmeldung)

\_\_\_\_\_  
(Day/Month/Year Filed)  
(Tag/Monat/Jahr der Anmeldung)

<input checked="" type="checkbox"/>	<input type="checkbox"/>
Yes	No
Ja	Nein
<input type="checkbox"/>	<input type="checkbox"/>
Yes	No
Ja	Nein

Ich Beanspruche hiermit Prioritätsvorteile unter Title 35, US-Code, § 119(e) aller US-Hilfsanmeldungen wie unten aufzählt.

I hereby claim the benefit under Title 35, United States Code, § 119(e) of any United States provisional application(s) listed below.

\_\_\_\_\_  
(Application No.)  
(Aktenzeichen)

\_\_\_\_\_  
(Filing Date)  
(Anmeldetag)

\_\_\_\_\_  
(Application No.)  
(Aktenzeichen)

\_\_\_\_\_  
(Filing Date)  
(Anmeldetag)

Ich beanspruche hiermit die mir unter Title 35, US-Code, § 120 zustehenden Vorteile aller unten aufgeführten US-Patentanmeldungen bzw. § 365(c) aller PCT internationalen Anmeldungen, welche die Vereinigten Staaten von Amerika benennen, und erkenne, insofern der Gegenstand eines jeden früheren Anspruchs dieser Patentanmeldung nicht in einer US-Patentanmeldung, bzw. PCT internationalen Anmeldung in in einer gemäß dem ersten Absatz von Title 35, US-Code, § 112 vorgeschriebenen Art und Weise offenbart wurde, meine Pflicht zur Offenbarung jeglicher Informationen an, die zur Prüfung der Patentfähigkeit in Einklang mit Title 37, Code of Federal Regulations, § 1.56 von Belang sind und die im Zeitraum zwischen dem Anmeldetag der früheren Patentanmeldung und dem nationalen oder im Rahmen des Vertrags über die Zusammenarbeit auf dem Gebiet des Patentwesens (PCT) gültigen internationalen Anmeldetags bekannt geworden sind.

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PCT/EP00/06133

\_\_\_\_\_  
(Application No.)  
(Aktenzeichen)

June 30, 2000

\_\_\_\_\_  
(Filing Date)  
(Anmeldetag)

\_\_\_\_\_  
(Status) (patented, pending, abandoned)  
(Status) (patentiert, schwebend, aufgegeben)

\_\_\_\_\_  
(Application No.)  
(Aktenzeichen)

\_\_\_\_\_  
(Filing Date)  
(Anmeldetag)

\_\_\_\_\_  
(Status) (patented, pending, abandoned)  
(Status) (patentiert, schwebend, aufgegeben)

Ich erkläre hiermit, daß alle in der vorliegenden Erklärung von mir gemachten Angaben nach bestem Wissen und Gewissen der Wahrheit entsprechen, und ferner daß ich diese eidesstattliche Erklärung in Kenntnis dessen ablege, daß wissentlich und vorsätzlich falsche Angaben oder dergleichen gemäß § 1001, Title 18 des US-Code strafbar sind und mit Geldstrafe und/oder Gefängnis bestraft werden können und daß derartige wissentlich und vorsätzlich falsche Angaben die Rechtswirksamkeit der vorliegenden Patentanmeldung oder eines aufgrund deren erteilten Patentes gefährden können.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.



## German Language Declaration

VERTRETUNGSVOLLMACHT: Als benannter Erfinder beauftrage ich hiermit den (die) nachstehend aufgeführten Patentanwalt (Patentanwälte) und/oder Vertreter mit der Verfolgung der vorliegenden Patentanmeldung sowie mit der Abwicklung aller damit verbundenen Angelegenheiten vor dem US-Patent- und Markenamt: (Name(n) und Registrationsnummer(n) auflisten)

POWER OF ATTORNEY: As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith: (list name and registration number)



**022850**

Postanschrift:

Send Correspondence to:



**022850**

Telefonische Auskünfte:  
(Name und Telefonnummer)

Direct Telephone calls to: (name and telephone number)

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Vor- und Zuname des einzigen oder ersten Erfinders	1-00	Full name of sole or first inventor	
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		Mannheimerstr. 59, 76337 Waldbronn, DE	DEX
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		same as above	
Vor- und Zuname des zweiten Miterfinders (falls zutreffend)		Full name of second joint inventor, if any	
Unterschrift des zweiten Erfinders	Datum	Second inventor's signature	Date
Wohnsitz		Residence	
Staatsangehörigkeit		Citizenship	
Postanschrift		Post Office Address	

(Im Falle dritter und weiterer Miterfinder sind die entsprechenden Informationen und Unterschriften hinzuzufügen.)

(Supply similar information and signature for third and subsequent joint inventors.)